Fire Risk Management Procedure for Valuable Contents in Historical Heritage Buildings

Dissertation

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*) Either the German or the Italian form of the title may be used.

Abstract

Heritage buildings are exposed to the same fire threats as others. This dissertation has the goal to provide a risk management procedure in order to improve fire protection of Valuable Contents contained in Historical Heritage Buildings. None specific Italian code or law have the building and content protection as its primary goal, but managers of historical buildings have however responsibility for the Valuable Contents inside the building. The core of the procedure is structured in two parts: 1.Risk Assessment; 2.Risk Treatment. In Risk Assessment phase, by means of a risk analysis and evaluation method, we want to point out which are the weak points in contents' protection due both to building features and to management strategies. The hierarchy structure is composed by 4 different levels: 1-Policy (target of the procedure); 2-Objectives (top parameters: Evacuation, Fire Brigade Effectiveness and Fire and Smoke Spread); 3–Characteristics (Technical Installations, Egress Paths, Structure, Height, Vertical Connections, Context); 4-Factors (total of 15 factors). To feed the Hierarchy Structure with reliable data, experts' judgments have been collected making use of a Delphi Method performed in Italy. The expert panel for this research has been selected among Italian academics, fire brigades and technicians involved in historical building's management: the tool is calibrated on the Italian situation. Results from Delphi have been used in the risk hierarchy calculation and a sensitivity analysis has been conducted to test the reliability of the structure. In Risk Treatment phase is proposed a strategy to choose the best set of mitigation measures to reduce risk for Valuable Contents. The procedure suggests to the user sets of coherent measures to mitigate specific risk indexes by means of managerial strategies and interventions on building. The procedure has been applied to two different historical buildings in order to compare outputs from the procedure with the expectations.

Sommario

Gli edifici storici sono esposti a minacce di incendio paria gli altri. Questa tesi ha lo scopo di fornire una procedura di gestione del rischio, al fine di migliorare la protezione dal fuoco di contenuti di valore all'interno degli edifici del patrimonio storico. Nessuna legge italiana ha la protezione dell'edificio e dei contenuti come obiettivo primario; i manager degli edifici storici hanno comunque la responsabilità di proteggere i contenuti di valore presenti all'interno dell'edificio. Il nucleo della procedura proposta è strutturato in due parti: 1-valutazione del rischio; 2. trattamento del rischio. In fase di valutazione, per mezzo di un metodo gerarchico di analisi del rischio, vogliamo sottolineare quali sono i punti deboli riguardo la protezione dei contenuti dovuti sia alle caratteristiche costruttive dell'edficio che alle strategie di gestione. La struttura gerarchica di riferimento è composta da 4 diversi livelli: 1-politica (target della procedura), 2-Obiettivi (parametri apicali: Evacuazione, Efficacia dei Vigili del Fuoco e Propagazione del fumo e delle fiamme), 3-Caratteristiche (Impianti tecnici, Vie d'esodo, Struttura, Altezza, Connessioni verticali, Contesto), 4-Fattori (15 sotto-parametri). Per alimentare la struttura gerarchica con dati attendibili, sono stati raccolti giudizi di esperti facendo uso di un metodo Delphi condotto in Italia. Il gruppo di esperti di questa ricerca è stato selezionato tra gli Accademici italiani, Vigili del Fuoco e Tecnici coinvolti nella gestione degli edifici storici: lo strumento è quindi calibrato sulla situazione italiana. I risultati del Delphi sono stati utilizzati nel calcolo della struttura gerarchica e un'analisi di sensitività è stata condotta per verificare l'affidabilità della struttura. In fase di trattamento del rischio si propone una strategia per scegliere il miglior set di misure di mitigazione per ridurre il rischio per i contenuti di valore. La procedura propone all'utente gruppi di misure coerenti per ridurre gli indici di rischio specifici attraverso strategie gestionali o interventi sulla costruzione. La procedura è stata applicata a due diversi edifici storici, al fine di confrontare i risultati ottenuti dalla procedura con le aspettative.

Zusammenfassung

Diese Arbeit hat zum Ziel, auf ein Risikomanagementverfahren bereitzustellen, um das Feuerschutz wertvoller Inhalte der historischen Gebäude zu verbessern. Kein italienisches Recht betrachtet den Gebäude- und ihen Inhaltsschutz als vorrangiges Ziel. Die Managers der historischen Gebäude haben die Verantwortung, die die innerhalb des Gebäudes befindenden Wertsachen zu schutzen. Der Kern des vorgeschlagenen Verfahrens ist in zwei Teilen gegliedert: 1. Risikobewertung; 2. Risikobehandlung. In der Evaluierungsphase werden die Schwachstellen durch eine hierarchische Methode der Risikoanalyse des Inhaltsschutzes betont. Diese Schwachstellen hängen sowohl von den strukturellen Merkmalen der Gebäude als auch von den Managementsstrategien ab. Die hierarchische Referenzstruktur besteht aus vier Stufen: 1. Politik; 2. Ziele; 3. Eigenschaften; 4. Faktoren. Um zuverlässige Daten in der hierarchischen Struktur einzufügen, wurden Expertenurteile durch den Einsatz einer "Delphi-Methode", der in Italien durchgeführt wurde. Die Gruppe von Experten dieser Forschung wurde zwischen Akademiker, Feuerwehrmänner und Techniker gewählt, die an der Verwaltung der historischen Gebäuden eingewickelt sind. Dieses Resultat wurde durch die Italienische Situation kalibriert. Die Ergebnisse der Delphi-Methode wurden in der Berechnung der hierarchischen Struktur verwendet, und schließlich wurde eine Sensitivitätsanalyse durchgeführt, um die Zuverlässigkeit der Methode zu überprüfen.

In der Risikosbehandlungsphase wird eine Strategie vorgeschlagen, um die beste Gruppe von Minderungsmaßnahmen zu wählen, um das Risiko für relevante Inhalte zu reduzieren. Die Praxis bietet Gruppen von Maßnahmen an den Anwender, um die spezifischen Risiko-Index durch gezielte Strategien und Interventionen auf dem Gebäude zu reduzieren. Das Verfahren wurde auf zwei verschiedenen historischen Gebäudenn aufgebracht, um die erhaltenen Ergebnisse mit den Erwartungen zu vergleichen.

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Tommaso Giusti
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Chapter 1

Preservation of Historical Heritage Buildings and Valuable Contents

During the recent decades and especially since the seventies, a great concern about the Conservation and Preservation of Cultural Heritage has appeared in many countries. This universal concern has different reasons, among them the fact that many historic monuments have been compromised by a messy urban development.

1.1 Protection of cultural heritage

The memory of a nation is based on its technical and cultural creations of the past [93, 92]. A gap in the historic continuity of the nation is created, if these monuments or works of art disappear. As a consequence of that gap, social life is disarranged, so that sometimes society is forced to create substitutes. That is the reason why Poland, a country that was totally destroyed after the Second World War, decided to rebuilt its town and monuments in the pre-war style [93]. The protection of monuments and their valuable contents is a necessity scooping to the preservation of historic heritage and the transmission from one generation to the next, in order to preserve the cultural identity and continuity of nations and societies through the years.

The erection of a monument does not automatically assure its maintenance through time. It mainly depends on the consideration given by future generations, that is to say, in which degree a society can evaluate cultural values of the past, how far these values can resist time. As reported in [92], Goethe expressed for the first time in 1798, in the introduction of his work "Propylën", another concept for the cultural creation, referring that:

> *"[...] everything that man is thinking or is creating belongs to humanity and every human effort which could be used by humanity, brings her into humanity."*

In this way, the meaning of universality of arts and science is introduced. This concept survives till today and is included in international conventions and agreements for monuments conservation.

1.2 International conventions and agreements

From Papaioannou [92], it is possible to identify the "Swedish law", in 1866, as the first legislation on conservation of national monuments. Then, in the beginning of XX century, International Agreements referred to protection of cultural heritage from war damage were published. In Athens Congress of 1931, the concept of an international cultural inheritance with specific general principles was for the first time emphasized. That was imprinted in a vote accepted by the Society of Nations Assembly, in 1932. A relevant indirect reference was made again in the international meeting of architects (C.I.A.M.) in Athens (1933). They specified the basic principles of urban planning in the so called "Charter of C.I.A.M.". A significant step for monuments protection in the period of war operations was "Hauge Convention" signed in 1954, with initiative of UNESCO. So we reach 1964, when the second Congress of Architects and Experts in Historic Monuments takes place in Venice. There were 13 Resolutions in that Congress. The first of them is known as "International Restoration Charter" or **Charter of Venice** [108]:

> *Preamble*
>
> *Imbued with a message from the past, the historic monuments of generations of people remain to the present day as living witnesses of their age-old traditions. People are becoming more and more conscious of the unity of human values and regard ancient monuments as a common heritage. The common responsibility to safeguard them for future generations is recognized. It is our duty to hand them on in the full richness of their authenticity. [...]*

It is defined in that text the meaning of historic monument, which does not cover only architectural creature but the whole urban or rural area as an evidence of a historic event or a specific civilization. That does not only refer in the famous creations but also in the modest anonymous works that gained through the time a cultural value. Restoration and conservation of monuments have the task to conserve them as works of art and historic evidence. Various definitions exist in different countries on terms concerning restoration and conservation (preservation, reconstruction, sanitation, rehabilitation, anastylosis, etc.). Charter of Venice constitutes the framework of international architectural heritage conservation principles.

Always according to Papaioannou [92], the "Convention of Archeological Heritage Protection", signed in London in 1969, is identified as the next general international document after Charter of Venice. Three years later, **Convention of Universal Cultural and Natural Heritage** [113] of the United Nations is signed in Paris (November 1972). 1975 was affirmed by the Council of Europe to be the year of European architectural heritage conservation. The most eminent manifestation in this year was the Congress of Amsterdam and the homonymous declaration consisting the **Charter of Architectural Heritage** [44], signed by 21 nations.

A very important step for architectural heritage conservation was the European Council Ministers meeting held in Granada of Spain on October 1985. There were representatives from the - at that time - 21 member states of European Community, who signed the **Con-**

vention of European Architectural Heritage Protection [45]. This is still now the frame of a common policy for the conservation and the distinction of European Architectural Heritage. In that convention dilated meanings of monument, architectural complex and historic site, which include not only archaeological and artistic masterpieces, but also buildings, complexes or areas with a special scientific, social or technological interest were established. Member states undertook the duty to make registration and complete documentation of their national monuments. A relevant legislation on conservation with proper mechanisms of practical application, control and penalties should be applied. Finally, the need of a national and international cooperation among conservationists, architects and other experts, and of a mutual technical assistance and exchange of information and experience was emphasized.

The latest chain link in the long history of heritage conservation, is the **Council Framework Convention on the Value of Cultural Heritage for Society** [43] (signed in Faro, October 27th 2005). The Council of Europe had the aim to emphasize the value and potential of cultural heritage that have to be wisely used as a resource for sustainable development and quality of life in a constantly evolving society. With the 2005 convention is recognized the need to put people and human values at the centre of an enlarged and cross-disciplinary concept of cultural heritage; another step towards the creation of a pan-European framework for co-operation in cultural heritage protection. Below is an extract from the Council Framework Convention on the Value of Cultural Heritage for Society:

> ***Article 1. Aims of the Convention***
> *The Parties to this Convention agree to:*
>
> 1. *recognise that rights relating to cultural heritage are inherent in the right to participate in cultural life, as defined in the Universal Declaration of Human Rights;*
> 2. *recognize individual and collective responsibility towards cultural heritage;*
> 3. *emphasize that the conservation of cultural heritage and its sustainable use have human development and quality of life as their goal;*
>
> *[...] .*

1.3 Definitions

Speaking about conservation of historical heritage we refer, as widely said, both to buildings and their contents. We must use a common language, which has been established by the conservationists during many years and is written in several international texts (Conventions, Agreements etc.).

CONSERVATION

Conservation is defined as the technical intervention to protect a historic monument or a traditional or listed building from dilapidation. Below text extracted from the Charter of Venice, with comments:

ARTICLE 4. It is essential to the conservation of monuments that they be maintained on a permanent basis.

ARTICLE 5. The conservation of monuments is always facilitated by making use of them for some socially useful purpose. Such use is therefore desirable but it must not change the lay-out or decoration of the building. It is within these limits only that modifications demanded by a change of function should be envisaged and may be permitted.

It has to be noticed the importance of the compatibility between present use and historic destination of use. Usually giving a modern destination of use to ancient buildings can lead to make interventions on the lay-out of the building.

ARTICLE 6. The conservation of a monument implies preserving a setting which is not out of scale. Wherever the traditional setting exists, it must be kept. No new construction, demolition or modification which would alter the relations of mass and colour must be allowed.

It is important to take the less invasive actions in order to conserve the building integrity.

ARTICLE 7. A monument is inseparable from the history to which it bears witness and from the setting in which it occurs. The moving of all or part of a monument cannot be allowed except where the safeguarding of that monument demands it or where it is justified by national or international interest of paramount importance.

ARTICLE 8. Items of sculpture, painting or decoration which form an integral part of a monument may only be removed from it if this is the sole means of ensuring their preservation.

It is important to conserve the building with all its artistic contents and architectonical features.

RESTORATION

"We usually consider as restoration every action done with the aim to give new efficiency to a product of human activity". This definition of restoration, given by Brandi [36], is the most general definition of restoration that can be given. Such a sentence has intrinsically a lot of unsolved issues, starting from the expression "to give new efficienc". Is it simply possible to re-establish objects functionality or to re-establish objects usability? Each one of the aims brings to different behaviours in acting on cultural objects (both works of art and heritage buildings).

MONUMENT

Monument is defined in the first article of the Charter of Venice:

> [...] *ARTICLE 1. The concept of an historic monument embraces not only the single architectural work but also the urban or rural setting in which is found the evidence of a particular civilization, a significant development or an historic event. This applies not only to great works of art but also to more modest works of the past which have acquired cultural significance with the passing of time.* [...]

The following are considered as the main characteristics of a monument (conditions *sine qua non*) [93]:

1. Originality. Which refers to the special value of every monument, that could not be repeated even in the case of a precise copy, since it includes a correlation of those components and parameters consisting an original creation.

2. Time (historicity). Which includes all time phases and interventions to the monument, giving the chronological sequence of events in the life of the creature.

3. Quality. Which is difficult to be defined since the elected evaluation system is several times subjective depending on the ideology and the aesthetic criteria of every society and each period.

4. Symbolism (message). This criterion was added in order to declare the message from the past contained in the monument and it is expressed with each accurate form

WORK OF ART

The concept of work of art (WoA) is strictly linked (if almost not intrinsically comprehended) with the previous definitions. In order to define Conservation, Restoration and Monument we need to have clear in our mind what a Work of Art is. From Brandi [36]:

> *"'[...]As a product of human activity, work of art is composed by a double essence: aesthetic essence, that corresponds to the fact of artistry, that change a work into a work of art; historic essence that put the human product in a certain time period and place, work of art that in a certain time and place stands. [...] Restoration is the methodological moment of the work of art identification, in its physical consistency and in its double essence, aesthetical and historical [...]"*

The difference between physical consistency of the works of art and their essence is usually a parameter employed to estimate importance of works of art in case of fire. On one hand, with respect to the fire event, any work of art reacts with its physical consistency; on the other hand, the damage of a work of art due to smoke or fire is mainly a damage to its essence (historical and aesthetical).

VALUABLE CONTENTS

To define Valuable Contents it is necessary to refer to the previous definition of Work of Art. The object of this dissertations are Historical Heritage Buildings (ref. following definition) containing Works of Art and the main objective is to mitigate fire risk to which

they are exposed. From the above definition, Work of Art has two essences: the physical and the aesthetic one. A risk manager has to be interested in both aspects but, as a technician, he is used (and he has competency) to manage only the physical aspect. It is necessary to leave the definition of "aesthetic essence" to art historians, or at least collaborate with them. This is the reason why, in the follow of this thesis, every time we refer to contents importance (or value) we'll adopt definitions and rankings given in Cost C17 [86], a European research program involving art historians to estimate damages due to fire in historical buildings (for a detailed Cost C17 description refer to section 3.1). We'll manage the "physical essence" of the assets because the material, the shape and the dimension of the object are involved in fire event, and it is the "physical essence" that take part to the Damage determination (ref. Definition 2 in chapter 2, section 2.1). Since we have the necessity to link Damage and Losses (ref. Definition 3 in chapter 2, section 2.1), we need to involve the "aesthetic essence" referring to conventional criteria accepted by art historians.
We refer to Valuable Contents when we have physical objects (wooden or textile pictures, statues, jewels, and other mobile items) that can be classified with the"importance criteria" given by art historians in Cost Action C17 "Executive Summary of Recommendations", [86].

HISTORICAL HERITAGE BUILDING

Historical Heritage Building (HHB) is in this dissertation defined as: an historical building (sites and areas are not comprehended) that is considered a monument because of its fabric and its contents and/or its destination of use. For Historical Heritage Building we consider here a building that has:

- an intrinsic historical value linked to its life through centuries;
- an intrinsic artistic and architectonical value due to building's fabric;
- a social value;
- a cultural value.

We are here interested in HHBs containing Valuable Contents. Valuable Contents intrinsically linked to the building (frescos, tapestries, decorations, etc.) are indirectly considered among the building's architectonical features.

MANAGER OF HISTORICAL HERITAGE BUILDINGS

In this dissertation we'll refer to Italian situation in defining 'HHB manager" in the acceptation we'll use all along this thesis. Since we refer to the link between Historical Heritage Buildings and Valuable Contents protection, we can base our definition on the "museum manager" definition given by Italian law.

From Italian law about museum's management standards "DM 10/05/ 2001" [11] :

> *"[...]The multiple functions of the museum (primarily conservation and collection management, access and services to the public, safety, research) may*

be carried out only if the museum has qualified personnel. [...] to protect the collective interest, must be complied with certain rules covering: [...]- the full responsibility of the director in front of the organ of government and control of the museum, especially for choices of technical-scientific nature [...]"

From Garlandini [59] this definition is here related:

> *The Museum manager is responsible for the museum as part of the mission he or she is entrusted by the owner and/or operator. He/she defines the strategic decisions for the promotion and development of the institution. He/She is responsible for the collection and quality of activities and services of the museum.*

He/she has a triple function of guidance and control systems [99].

- Science: he/she defines and monitors the activities related to collections and their enrichment, and he/she supervises and contributes to the conservation, study, safety and development of collections. He/she establishes guidelines for research institute.
- Cultural: he/she defines the overall plan of activities related to the presentation of the permanent and temporary exhibits and promotes public access to the museum and its services.
- Managerial: he/she coordinates the different services of the museum and has the responsibility for human resources management, technical and financial. He/she ensures the relationships with local owners. He/she represents the museum at the different institutions and partners, both public and private. He/she ensures the continuous assessment of the activities of the museum.

Manager in State Museums
Italian law 42/2004 does not provide the figure of the "museum manager" for state museums. State museums are managed in a "museum office"' way by the *Soprintendenza* and manager function is carried out, among his many duties, by the *Soprintendente* or one or more delegates.

More in general terms, we'll define in this dissertation a "HHB manager" as the person, or the group of persons, that has the following responsibility:

- <u>Administrative responsibility</u>
  implementation of administrative procedures for management. Define of objectives and address the programmatic management of capital goods. Implementation of programs and projects.
- <u>Economic and financial responsibility</u>
  Economic planning and multi-annual management of economic and financial resources.

- Institutional responsibility
  Official representative of the museum (as delegated by policy).

- Responsibility in human resource management
  Procedures for recruitment, human resources management and organization. Training and retraining of personnel.

- Responsibility for real property, furnishings and equipment
  HHB: technical plans, fittings, equipment. Routine maintenance and repairs.

- Safety Responsibility
  Safety of occupants (employees and visitors). Fire prevention.

- Responsibility on mobile contents
  Management of collections. Management of in storage and on loan collections, presentation and exhibition of heritage. Relations with the Superintendents. Security of the museum's heritage (theft and damage). Restoration and conservation.

1.4 Historical Heritage Buildings in Italy

In each European country there are specific laws defining heritage buildings and "items" [85], [97], [128], [94]. The first Italian Law defining either rules to identify "items" (buildings, goods, paintings, collections, etc.) to be considered of historic and/or artistic interest and to protect them, was Legge n.1089 issued in 1939 [2]. According to this Law all public property "items" older then 50 years and whose author was not any more alive, had to be considered of historic and/or artistic interest and consequently protected. Each public owner would have to compile a list of the "items" belonging to him and send it to the competent Minister. These public "items" could not be sold.

For private property "items", it was necessary that the Ministry notified to private owners the "binding force" of historic and/or artistic interest. This "binding force" could be consequent to a notice sent by a public or private subject or, for special kinds of "items" (as collections of pictures or books or archaeological elements, etc.), it was consequent to the compulsory declaration produced by the private owner. These private "items" could be sold following particular rules. For all these "items", of public or private property, the Law defined the rules to be followed for their conservation and protection. In 1939 too was issued Legge n.1497 [3] to protect "beauties of nature". This Law defined requisites that a natural site had to satisfy to be considered something to be protected. Even if these were the most important Laws concerning conservation, during the years different kinds of Acts have been issued relating to specific aspects on the same themes: funds to be utilized for conservation works, methods to follow for works to be approved and so on.

Things remained essentially unchanged even when in 1999 D.Lgs n.490 [10] was issued to re-order the sector, through a single Act, replacing about all previous legislation. Few years ago a new special Law, D.Lgs n.42 [16] titled "Codice dei beni culturali e del paesaggio" re-ordered again the matter replacing the previous D.Lgs n.490 issued in 1999. Substantially, according to this new special 2004 Law, the previously defined criteria to identify the “items” to be considered of historic and/or artistic interest have remained unchanged with the only main difference that not necessarily all public property “items” older than 50 years and whose author is not any more alive has to be considered of historic and/or artistic interest. In fact, according to this new 2004 Law, the competent Ministry has to analyse all the description forms (that have to be compiled by the public or private owners) concerning each “item” in order to verify the historic and/or artistic value of them. If there are the necessary requirements, the Minister issues a “cultural interest declaration” and the “item” is included in specific ministerial lists concerning protected “items”. If not, the “item”, even if of public property and older than 50 years and whose author is not any more alive, has not to be considered something to be protected and can be too sold to private owners. In Italian heritage are comprehended at least 95.000 monuments and churches, 30.000 historical buildings, 3.500 museums, 2.000 archeological sites and 900 theaters.

1.5 Fire in historical buildings

Fire was one of the most serious threats for the buildings and sites through the centuries. Although most of historic buildings were built in periods when very poor, if not at all, Fire Codes and Standards were applied, many of them exist now in their original condition after such a long time. That happens because, on one hand, the traditional builders and architects applied several sophisticated fire protection measures based on the state of the art at that time as well on common sense, and on the other hand, after major fires and conflagrations, the authorities put in force more severe and more developed fire protection legislation. Historic buildings by their nature vary in age, use and construction. However, they all share the common threat of damage or total loss by fire. The threat of fire is omnipresent and consequential damage may be catastrophic: hence the need to manage continuously the risk of fire at all levels within the existing national structures. An historic building constitutes a complex environment with regard to the building, building’s fabric, contents and people (where the public have access) that must be effectively and sympathetically integrated [109]. The dimensions of this complex environment and associated impacts are illustrated in Figure 1.1.

Although fire safety objectives have been expressed in different ways by different authorities in different countries, generally there are accepted two main aspects of fire protection for modern buildings: **life safety** and **property protection**. For historic buildings the **protection of cultural values** must be added either for the buildings or for their contents. It is not possible to achieve an absolute fire safety. In most cases, a proper fire safety design assume that a limited unwanted fires will occur and proper means shall be provided to minimize the losses from fire till an acceptable level.

Below is a list of the main fire events in Historical Buildings. The first group comprehends the so-called ”Monumental fires” in historic structures and cities that had an international fame [93, 110]; the second group refers to fires involving heritage buildings in Italy in the last years [30, 81, 101].

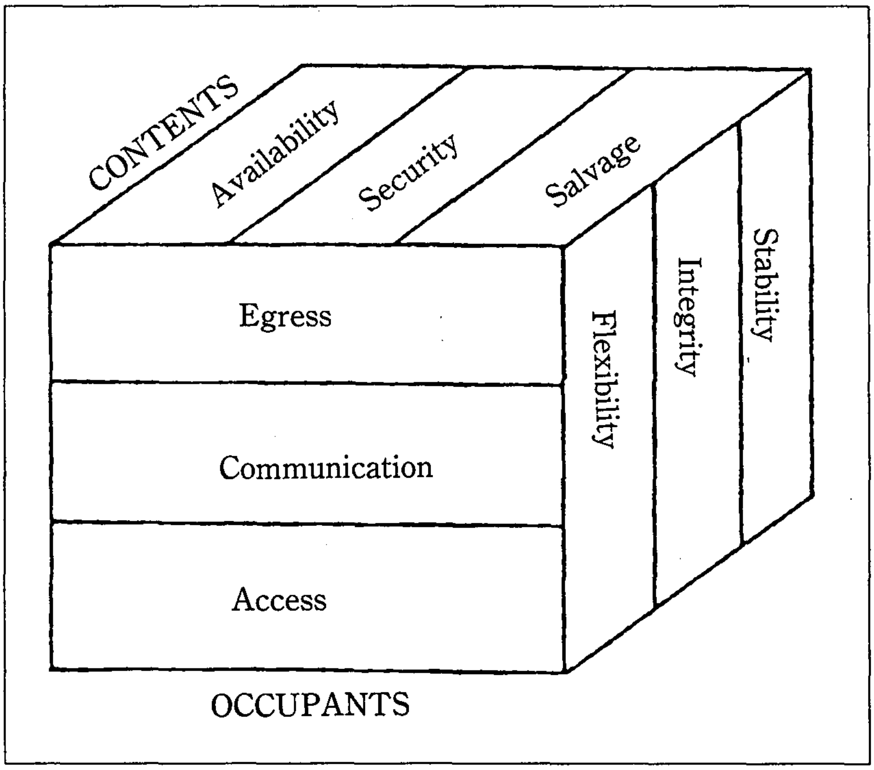


Figure 1.1: Conceptualisation of the complex environment created by historical buidings [109].

MONUMENTAL FIRES

- The fire of the wooden wall and of many temples of the Athenian acropolis by the Persians (480 B.C.-Herodotus, III 52). After this complete destruction of the first Parthenon, Athenians built the new Periclean Parthenon which, although heavily damaged through the centuries, survive up to now. Two large fires destroyed most of the valuable parts of the monument. The first one was put by the Celtic tribe of Eruls pyromaniacs on the year 267 A.D. The second fire was due to the Venetian F. Morosini (1687 A.D.), who bombed the temple of Parthenon completing the destruction of the Celts.

- Rome (Galatians 387 B.C.) - (Nero 64 A.D.)

- Library of Alexandria (Julius Cesar 47 B.C.-Aurelianus 270 A.D. - Serapeion 391 A.D. and Kalif Omar 641 A.D.)

- London Great Fire (1666) was the initiator of building regulations in England. The easterly wind assisted the fire spread and highlighted the need of buildings separation and the control of their walls and roofs ignitability.

- Jamestown, Virginia USA (1608)

- Plymouth, Mass. USA (1623)

- Manhattan New York, USA (1628)
- Edinburgh Great Fire (1824)
- Chicago, USA (1871)
- Aalesund, Norway (1904)
- Risor, Norway (1716, 1861)
- Thessaloniki, Greece (1917)
- Lisbon-Chiado, Portugal (1988)
- Windsor Castle (November 1992). Fire occurred in Windsor Castle, to the west of London, the largest inhabited castle in the world and one of the official residences of the British monarch, Elizabeth II.
- South Bridge/Cowgate -Edinburgh (2002)

RECENTS FIRES IN ITALIAN HERITAGE BUILDINGS

- October 27th, 1991: fire breaks out in the Petruzzelli theatre in Bari. The flames destroy all the internal structures and bring down the roof. Only the walls remain standing.
- December 4th, 1992: the Cathedral of Brescia is damaged by a fire that destroys among other things, a painting of the 7th Century, attributed to Paglia brothers, recently restored.
- January 29th, 1996: a fire almost completely destroys the Fenice Theatre in Venice. Also many historical documents preserved in the theatre end up in ash .
- April 12th, 1997: a fire severely damages the Turin Cathedral and the adjacent Royal Palace.
- June 27th, 1998: a fire breaks out between the scaffolding raised on the facade of the Church of San Geremia in Venice, damaging it and partly damaging the wooden roof of the tower.
- November 4th, 1998: an outbreak of fire at the Royal Palace of Caserta, in the attic where rooms used by the Air Force airmen of the NCO School are located. On February 20th, 1999, in the same attic of the Palace another fire started.
- March 30th, 1999: a fire spreads to the French Academy in Rome, at the top of the Trinità dei Monti, a housing reserved for students in transit. No damage to the library, tapestries and works of art.

- June 27^{th}, 2002: a fire develops during the renovation of the theatre La Scala in Milan. The workers were working in the attic. They were dismantling the roof of the structure. It was a fire due to a slow-burning of seasoned wood: a lot of smoke but no flame. For this reason, none, realized the fact and gave the alarm for several hours. From this episode a permanent team of four Fire Department was set up, in order to oversee the construction site 24 hours out of 24. In addition, an official of the Fire Department takes part in regular meetings of the Coordination Committee of Safety.
- April 15^{th}, 2003: fire in Mulino Stucky of Giudecca, in Venice.
- December 27^{th}, 2010 a fire occurred in one of the major monuments in Lucca, the Guinigi chapel within the complex of San Francesco. The smoke has completely blackened medieval frescoes and decorations.
- August 29^{th} 2010 a fire has started at the roof level of the building near the Venice Salute Church. Firefighters have used large amounts of water to limit the spread of the blaze, in order to avoid the collapse of the roofs of the rooms of the church. The morning after the fire, the Titian (Tiziano Vecellio) painting "Davide and Goliath" has been removed from its location (in a room directly connected to the church main hall) in order to limit damages due to water used by firefigthers but the painting has been damaged.

Chapter 2

Risk Framework

2.1 Fundamentals in Risk Management

In emergency occurrence it is common to refer the need for management systems as a tool for risk reductions [58], [82]. However, risk should be first defined in order to become able to be reduced. According to Capone [37], the definition of risk strongly depends on the context where the object of study is located (i.e., financial-risk, environmental-risk, technical-risk, health-risk, social-risk). Therefore, a single definition of risk cannot always be applied. Within the work of Pliefke et al. [96] several definitions of risk regarding disasters were reviewed. Additionally, this study suggests that independent to the context of the object of study, the definition of *risk* should involve the terms of *hazard, loss, damage, vulnerability, exposure and consequences.* As specified in [67], a structured methodology for risk reduction is needed. In this sense, the PEER Equation (an earthquake engineering equation commonly used for risk reductions)is frequently referred, since it suggests a generalised methodology for decision-making regarding risk estimations and their probability of occurrence. In general terms, the PEER Equation considers the evaluation of a determined decision regarding specific risk by considering three main factors: (i) the specific hazard intensity, (ii) the response of the studied system (i.e., building location and design) to that hazard intensity and (iii) the potential damages and losses that the decision under consideration may overcome. Although the PEER Equation encloses a methodology, a non-rigorous mathematical expression is given:

$$g(\text{decision}) = \iiint p(\text{loss}) \cdot p(\text{response}) \cdot p(\text{damage}) \cdot p(\text{frequency}) \tag{2.1}$$

In this dissertation we'll refer to the terminology used in the standard ISO 10241 "International terminology standards - Preparation and layout" (1992 edition) [5]; indeed ISO vocabulary provides precise indications about some terms linked with fire risk analysis. "Fire danger" [ref. section 4.103 of ISO] is a concept containing both the potential fire danger, defined as "Fire hazard" [ref. section 4.112 of ISO] and the "Fire risk" [ref. section 4.124 of ISO]. Potential fire danger is defined as a "condition that can produce consequence" and it is not only linked with the "Fire load" [ref. section 4.114 of ISO] but also with management and organisation conditions, that can even worsen severity of consequences we expected after the fire. "Fire risk" is a concept that, according to equation 2.1, comprehends probability of occurrence and expected damages and/or losses. In particular, for the aim of this dissertation, it is possible to give the intuitive definitions reported in the following paragraphs.

Definition 1. (Probability)
Probability of fire occurrence (P) is in inverse proportion to *Prevention Measures*:

$$P \propto \frac{1}{PreventionMeasures} \tag{2.2}$$

Probability increases with the decreasing of prevention measures' application. In this dissertation the following prevention measures are considered:

- maintenance of technical installations;
- presence of fire compartments;
- Fire Service Team efficiency.

Definition 2. (Expected Damage)
Expected Damage (D) is in inverse proportion to *Protection Measures*:

$$D \propto \frac{1}{ProtectionMeasures} \tag{2.3}$$

The more are applied protection measures, the lower is the expected damage. In this dissertation the following protection measures are considered:

- technical installations for alarm;
- technical installations for detection;
- technical installations for suppression;
- technical installations for ventilation;
- Fire Service Team efficiency.

Expected Damage (D) is also proportional to the *Response* of the studied system, as referred in equation 2.1:

$$D \propto SystemResponse \tag{2.4}$$

Worst is the system behaviour in fire event, more severe will be the damage, and the opposite. Increasing of damage severity is linked to the features of the building we are studying. In this dissertation the following architectonic features are considered:

- height of the building;
- vertical connections;
- presence of double heights;

- destination of use;
- presence of chimneys and flues;
- position of the building with respect to the urban context;
- system of evacuation routes;
- structure.

Definition 3. (Expected Losses)
Expected Losses (L) are proportional to Expected Damage (D) and to Contents Vulnerability (V):

$$L \propto D \tag{2.5}$$

$$L \propto V \tag{2.6}$$

Definition 4. (Contents Vulnerability)
Contents Vulnerability (V) is in inverse proportion to Contents Importance (I):

$$V \propto \frac{1}{I} \tag{2.7}$$

The more are important the contents we want to protect, the lower is the level of Vulnerability we can accept. It means that for Contents with high Importance, since we want low Vulnerability, we need to have good Protection Measures. For the ranking of importance of Contents refer to page 90.

Definition 5. (Risk)
Depending on the considered parameters, risk will be expressed alternatively with the following expressions:

$$R = P \cdot D \tag{2.8}$$

$$R = P \cdot L \tag{2.9}$$

The Risk Management Chain Methodology (RMCM) published in [96] is here introduced as an alternative solution regarding the reduction of fire risk for Valuable Contents in historical buildings.

In general terms, the RMCM (Figure 2.1) consists of three main steps: risk identification, risk assessment and risk treatment. The first step (risk identification) corresponds to the identification of all the possible risks that may be present in the studied system, where the adequate system and boundaries definition is important. Once all the possible risks have been identified, each risk is analysed and judged. This corresponds to the so-called risk assessment. Meanwhile, risk analysis can be seen as the "operative step". Here the vulnerability of the system under specific hazards intensity can be quantified and potential damages or losses can be distinguished. At this point, all the risks are graded (for example, into low, medium, high or in any other scale) and compared with each other. With this information it is possible to distinguish between risks and to prioritise them. According to the relevance of the risk and its influence into the system, they can either be mitigated,

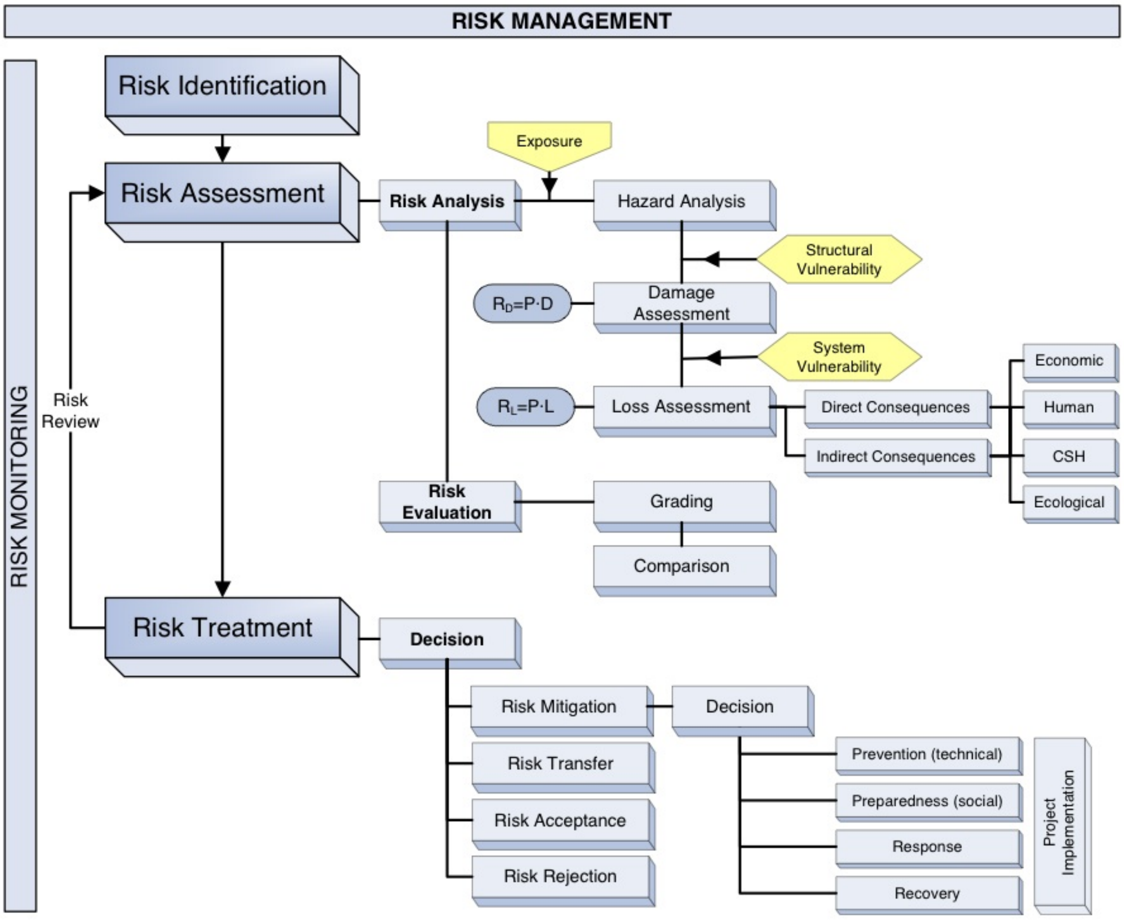


Figure 2.1: Overview of the complete Risk Management Chain Methodology regarding disasters, suggested in [96].

transferred, accepted or rejected (the so-called risk treatment). Only when it is decided to mitigate the risk, a preventive response and recovery phase can be implemented.

The proposed risk management procedure is built in accordance to the RMCM methodology, as shown in Figure 2.2. Risk identification is logically linked with fire. The first step of the procedure is the risk Assessment phase: it is based on a risk analysis process (identification of the element involved in fire risk) and on a evaluation process that let us estimate and judge all the identified risks. Between Assessment and Treatment there is a middle step, useful to evaluate risk acceptability respect to the stakeholders expectative. If risk is not acceptable, it is necessary to pass to the risk Treatment phase. In this phase Mitigation Measures are presented and estimated respect to their effectiveness on risk reduction.
The specific explanation about the structure of procedure is reported in chapter 4.

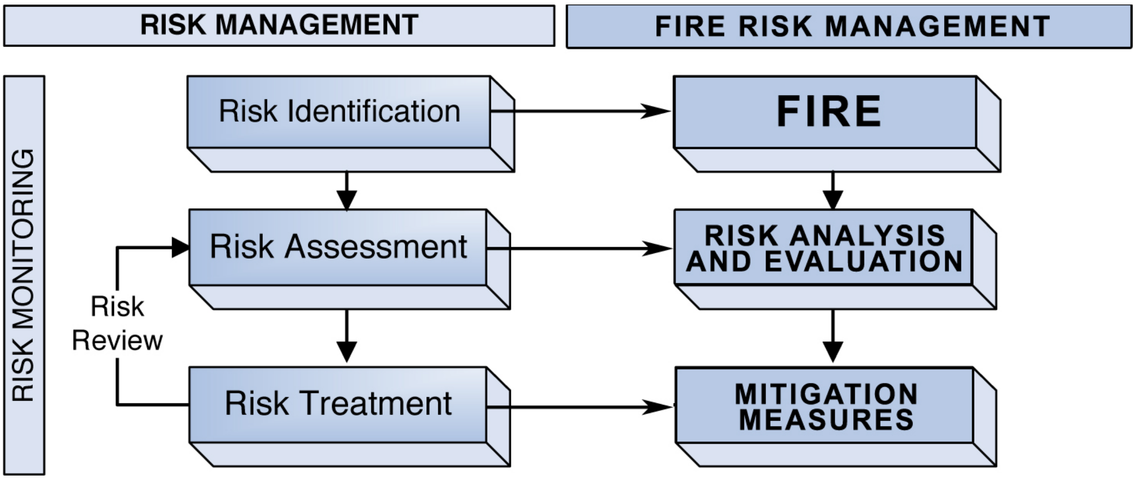


Figure 2.2: Connection between Risk Management Chain and Fire Risk Management Chain adopted in this dissertation, an elaboration from [96].

2.2 Fire Risk Assessment Methods

In this section some of the different existing fire risk assessment methods are reported. Over the years a great number of methods have been produced for almost all the kind of activities or buildings [53]. The most widely accepted and used risk assessment methods will be described in this section.
According to Larsson [74], methods for fire risk analysis may be classified into three categories:

- Regulations and checklists
- Ranking methods
- Quantitative methods

Fire risk assessment methods fitting historical buildings
Because of the different types of risk methods, there are some reasons for preferring a method to another as far as cultural heritages are concerned [15].

Acceptable features for a method are:

- people safety can be integrated in the same approach as property protection;
- the possibility to give an indication on arson;
- the possibility to have a cost estimate to risk assessment.

Reasons to disregard a method are:

- property protection is not one of the main goals. Methods used for people protection are less suitable as the principle that the building can be sacrificed for the safety of the people is often inherent to this approach;

- the effects to obtain an assessment should be balanced with the importance of the heritage to be protected. A method requiring a multidisciplinary team approach or a computer running during hours is not suitable for assessing risks for smaller buildings;

- cultural heritage is out of scope (i.e. a method deals with explosion risks in chemical industry);

- only one organisation as owner has the right to use a method and is not accessible on a broad basis.

Risk Management Methods' Criteria From FiRE TECH WG6 report [15], the main contents that a fire risk management method has to comprehend are here listed:

1. Identify fire hazards

2. Quantify consequence and probability of fire hazard,

3. Identify hazard control options

4. Quantify impact of options on risks of hazards

5. Select appropriate protection

2.2.1 Regulations and Checklists

A simple and safe way of achieving a satisfactory level of fire safety in a building is following carefully the existing building codes. This has very little in common with regular risk assessment methods, but it has to be mentioned here to illustrate the easiest way of solving the fire safety problems. An engineer (or in this case even a layman) just has to follow a number of detailed regulations and no "real" risk analysis is therefore necessary. Different types of checklists are often used as tools to make sure the building fulfils the building code. Checklists are (if they are adapted to a specific process, activity or building) often the fastest (and therefore often the best) way of identifying risk features. The main problem is that it is not possible to quantify the importance of such a feature. Another problem is that a checklist usually has to be very specific to be useful. Therefore different lists have to be developed and used for almost similar types of buildings. Since building codes have a long tradition, they were often introduced not based on traditional engineering estimates but on observations and experiences. The greatest disadvantage of just slavishly following detailed recommendations is the fact that every hazard situation shows a great variety in detail. In this approach it is desirable to choose a much more flexible method. Both regulations and checklists are non-quantitative approaches and may address the steps 1, 3 and 5 from paragraph *Risk Management Methods' Criteria* of Section 2.2, while bypassing steps 2 and 4.

2.2.1.1 NFPA 914 Code for Fire Protection of Historic Structures

The NFPA 914 Code for Fire Protection of Historic Structures [12] is to be seen as a regulation based on questions like narratives [15]. NFPA 914 contains fire protection guidelines, including the need to develop an overall fire protection plan and to emphasize the management responsibility to address fire protection and to preserve the historic integrity of the irreplaceable artefacts of history and culture. This document gives guidance on how to fullfil the regulations. Both a prescriptive approach as well as a performance-based approach are included, finding solutions to the life safety and fire safety problems in historic structures. In both cases, NFPA 914 has maintained the importance of preventing or minimizing the intrusion of the fire protection systems or solutions so as not to destroy the significance of the structure.

2.2.2 Ranking Methods

Ranking methods or semi-quantitative methods are today used in a wide variety of applications. Fire risk ranking is usually defined as a process of modelling and scoring hazard and exposure parameters to produce a rapid and simple estimate of relative risk. In short, fire risk ranking methods are, according to Watts [119], heuristic models which use professional knowledge and past experience to assign values to selected variables. Fire risk ranking methods have more often been developed with the purpose of simplifying the risk assessment process for a specific type of building, process etc. Quantitative methods often have been found to be too expensive and too time-consuming, which has led to a need of finding, or developing, a new risk ranking method which may be applied to the specific type of building, process etc. Ranking methods remove most of the responsibility from the user to the producer of the method. Usually a group of experts first has to identify every single factor that affects the level of safety/risk. The factors represent both positive features (increase the level of safety) and negative features (decrease the level of safety). The experts then usually decide the importance of each attribute, i.e. a value is assigned to each one. The values are usually based on the knowledge and the experience of a panel of numerous experts. The different knowledge and experience of the members of the panel is, in some way, a step towards reliable results. The assigned values are then operated by some combinations of arithmetic functions to get to a single value. The value, often called "risk index", is a measure of the level of safety/risk in the object and it is possible to compare this to other similar objects and/or to a stipulated minimum value. To simplify the ranking procedure for the user, who is often unfamiliar with ranking methods, some sort of rating schedules, grading schemes etc. are usually incorporated into the method. The greatest advantage of fire risk ranking methods is probably their simplicity. Thanks to the rapid risk assessment, fire risk ranking methods are considered to be very cost-effective tools. However, a demand on a ranking method should always be that the received results should not suffer too much from the simplicity of the method. Another positive side of fire risk ranking is the structured way in which the decision making is treated. This facilitates the understanding of the system for persons not involved in the development process and makes it easier to implement new knowledge and technology into the system. In Table 2.1, elaborated from [15], there is an overview on the different existing ranking methods and their ability to meet the acceptance criteria, reasons to disregard the method or positive features of the method and references.

Name of the Method	**Meets criteria on page 18**	**Negative features**	**Positive features**	**Reference**
Risk Value Method	Not the 5th criterion			[13]
FSES: Fire Safety Evaluation System	yes	It is not aimed at property, but at life safety		[119]
Specific Commercial Property Evaluation Schedule	yes		Cost of insurance	[119]
Dow Fire and Explosion Index (FEI)	yes	Cultural heritage is out of the scope		[119]
XPS FIRE	yes	Owned by Munich Re		[7]
Hierarchical Approach	yes	Workforce required: Delphi panel		
SIA 81	yes		Insurance premium related	[55],[114]
FRAME	yes		Life safety and business risk included, insurance premium related, arson clue	[51, 53]
FRIM	yes		Easy to handle	Ref. paragraph 2.2.2.1 of this dissertation

Table 2.1: Overview on the different existing ranking methods, elaboration from [15].

2.2.2.1 FRIM MAB

FRIM MAB (Fire Risk Index Method for Multi-storey Apartment Buildings) was developed by Department of Fire Safety Engineering in Lund University, [77, 74, 64, 68, 40, 35, 79, 69]. The method was created within the project called "Risk Assessment of Timber-frame Multi-storey Apartment Buildings Using a Risk Index method". The project is a part of the Nordic Wood bigger project named "Fire-safe Wood Frame Multi-storey

Apartment Building". The main fire safety objectives of FRIM MAB, as reported in [64], are deemed to be:

- Provide life safety
- Provide property protection

The Index method is based on a hierarchy structure for the fire safety in a building with wooden structure. The Index method was developed together with a Nordic project group, using a so-called Delphi panel for fine-tuning the method and defining the weights. The Delphi panel was made up of 20 Nordic experts who work with fire safety in various areas (consultancy, fire brigade, fire testing, fire research and insurance), [69]. The grades and weights are multiplied giving a relative value for each parameter. The sum of these weighted grades results in a single index value for the whole building which can be used to compare with index values for other buildings or different fire safety measures. Basic requirements in the building law must be definitely fulfilled.

To evaluate the FRIM MAB, a quantitative risk analysis (QRA) was carried out on four multi-storey timber-frame buildings, at that time constructed in four Nordic countries. Both the index method and the quantitative risk analysis were used to rank the buildings with respect to fire risk. The comparison showed a reasonably good agreement, keeping in mind that the two methods are very different in nature.

The index method can be used directly on all multi-storey apartment buildings and to derive a fire risk index demands that the user is an engineer or has some background in fire safety, [74].

As previously said, the hierarchical approach was found to be the most appropriate risk assessment methodology for application to multi-storey buildings. In the pilot study Magnusson and Rantatalo [79] suggested a generalized five-step process for ranking the attributes.

The procedure that Magnusson and Rantatalo used in the pilot study had the following steps:

- **Step 1: Identify hierarchical levels of fire safety specification**
  Magnusson and Rantatalo preliminary formulated the Policy as: "Fire safety performance for a wood-frame building should be at least equivalent to that of corresponding building with a non-combustible frame." The Policy could be expressed in terms of the following Objectives:

  1. Provide life safety
  2. Prevent fire spread from room of origin
  3. Prevent fire spread to adjacent building

- **Step 2: Specify attributes comprising each level**
  This is the most important and difficult part of the development process. The list has to be complete; it means that no major features are allowed to be left out, but

at the same time the list has to be easy to grasp and, if possible, to mathematically quantify. Usually some sort of matrix operation is used and therefore the wish is to restrict the number of attributes if possible. It may include statements about life safety, property protection, continuity of operations, environmental protection, and heritage preservation.

The NFPA Fire Concepts Tree was used when defining the list of Strategies. The Objectives above were found to depend on the following Strategies:

"Provide life safety":

- Control fire growth (S3)
- Establish safe egress (S1)
- Establish safe/effective rescue operation (S2)

"Prevent fire spread through compartment boundaries":

- Control fire growth (S3)
- Prevent fire spread through room boundaries (S4)
- Prevent fire spread through joints and intersections (S5)

"Prevent spread through building structure":

- Prevent fire spread through/in concealed spaces (S6)
- Prevent ignition of structure (S9)
- Prevent fire spread through window openings, facades (S7)
- Prevent fire spread to/through attic (S8)

"Prevent fire spread to adjacent building":

- Limit size of exposing fire (burning building) (S10)

The next level, referred to as the Parameter-level, consists of individual features that are measurable, directly or indirectly. The Parameters contribute to the achievement of the Strategies and thereby also to the achievements of the Objectives and the Policy. In pilot study 13 main Parameters that significantly influence the fire risk in a multi-storey timber-frame apartment building were identified.

- **Step 3: Assign weights to the attributes listed above**
These weights are always the same for a specific group of buildings, i.e. in FRIM MAB approach multi-storey apartment buildings. Once the structure of the index method has been determined to the objectives, strategies and parameters are given Weights. The Weights are determined by a Delphi method. As a result of Delphi, each of the Parameters have Weights that are linked to each one of the Strategies and the Strategies will have Weights linked to each one of the Objectives, etc. Thus, the relative importance of each parameter can be calculated through matrix multiplication, resulting in the index method.

- **Step 4: Develop a numerical scale on which the attributes can be assigned values or measures**
  The values are individual for each building.

- **Step 5: Select an evaluation model**
  Select a mathematical model that combines weights and values for each attribute and combines the different attributes to receive a single value. In FRIM MAB an Analytical Hierarchy Process was chosen.

Advantages and disadvantages
In agreement with [64], it is possible to affirm that FRIM MAB is only applicable to multi-storey apartment buildings with timber structure. Parameters, weights and indexes are strictly linked to the reality of such building typology.

Any engineering method, in any engineering discipline, can be misused and so the Index method presented here can. It is quite possible to achieve a good index rating by giving some parameters a very bad rating and other parameters a extremely good rating. For example, an engineer may give full marks for detection but zero marks for a signal system, indicating a design where fires are detected but no warning signal is given. In spite of the good index rating, the resulting building design may be totally unacceptable or absurd from a fire safety point of view. But this is only possible if the engineer really wishes to misuse the method. The building design and the use of the method must therefore be based on common sense, as it is true for most methods in all the engineering disciplines.

It is also important to note that the FRIM MAB is not an engineering design method. For example, if a designer wishes to reduce the minimum separation distance from other buildings, as prescribed in the building regulation, radiation calculations and a special window glass may be used in order to "prove" that the separation distance can be reduced. The designer cannot use the index method as a design method, but must use proper design methods.

2.2.3 Quantitative Methods

In an increasing number of countries the situation for building engineers and fire protection engineers has gone through a rather radical change. By the introduction of performance-based criteria for fire safety, it is now up to the engineer to verify that the level of fire safety in the building is equivalent to a building built according to current building codes. The engineer has to rely more on his own knowledge, which means that considerable responsibility has moved over to him/her personally. At the same time the freedom has increased, the engineer is free to use the tools he/she thinks are necessary. In many cases the engineer chooses to only evaluate a small number of the most likely scenarios. Computer models have then become a valuable tool for simulation of fire and smoke spread, evacuation etc. When calculating the total risk or the risk for a single scenario in more complex situations, an event-tree analysis is often the best tool. (Event-trees and other risk assessment methods are described in [15], [35], [63]). Fault-tree analysis is another example of a similar risk assessment method [112]. The term "deterministic methods" is

often used when referring to this type of methods. Perhaps the most time-consuming and complex way of evaluating the level of fire risk is to use a probabilistic method. One of the disadvantages is that the methods require a large base of input data. The engineer also has to be familiar with different mathematical techniques as for example stochastic modelling and linear regression. The advantage is the precision in the results. It is important to remember that no method or technique is the perfect choice in every situation, the most appropriate method has to be chosen from case to case. A probabilistic or deterministic method is very often the choice when the risk has to be known as accurately as possible. On the other hand, in many cases these methods are too complex, time-consuming and costly.
In this specific approach the objective has been to find an assessment method which is rapid and easy to use, i.e. one should not have to be a fire safety expert to be able to use it in a satisfactory way.

Probabilistic methods are the most informative approaches to fire risk assessment in which they produce quantitative values, typically produced by methods that can be traced back through explicit assumptions, data and mathematical relationships to the underlying risk distribution [60]. The following table Table 2.2, elaborated from [15], gives an overview on the different existing quantitative methods and their ability to meet the acceptance criteria, reasons to disregard the method or positive features of the method and references.

Name of the Method	**Meets criteria on page 18**	**Negative features**	**Positive features**	**Reference**
CRISP: Computation of Risk Indices by Simulation Procedures	yes	Aimed at life safety		[66]
FiRECAM: Fire Risk Evaluation and Cost Assessment Model	yes	For office buildings	Cost estimate (based on Canadian Market)	[129]
BFSEM: Building Fire Safety Evaluation Method	Not the 5th criterion		Cost of insurance	
FIERAsystem: Fire Evaluation and Risk Assessment	yes	Use for light industrial buildings		[74]
Event Tree Analysis	yes		Life safety, damage area, cost benefit analysis included	[15]
Fire Risk Assessment with Reliability Index β	yes	Complex and time consuming		[15]

Table 2.2: Overview on the different existing quantitative methods, elaboration from [15].

Chapter 3

State of the Art

"Conservation of Cultural Heritage" is a stated goal of the ISO Technical Committee on Fire Safety Engineering [120]. Heritage buildings are exposed to the same fire threats as other buildings, including arson, lightning, construction operations, faulty equipment, and inadequate maintenance [118]. Many specific aspects of the fire problem are unknown because statistically, heritage buildings are almost invisible. Fire loss data is typically collected only on factors that relate to fire cause and origin, building occupancy or building use. There is usually no fire loss data by historic significance or even building age.

The way we know about fire losses of heritage buildings is by observing those that occur around us or from media attention to those that are of such importance that they are newsworthy. Preserving our heritage from fire is a topic that is currently being addressed around the world, but in Europe in particular. In early Nineties the CIB W014 Working Commission identified seven projects as those of highest priority, including a "guidance document on rational fire safety engineering approach to fire safety in historic buildings". This represented ongoing work that was initiated some ten years earlier [80]. Other European activities included a Conference on Fire Protection and the Built Heritage held in Edinburgh, Scotland in 1998 and the Third International Symposium on Fire Protection of Heritage held in Warsaw, Poland in 1999. In 2000 the CIB co-sponsored the International Conference on Fire Protection of Cultural Heritage in Thessaloniki, Greece [93].

In addition to loss by fire, historic buildings are also vulnerable to another type of destruction, that is caused by a lack of understanding of how design professionals should respond to the unique configurations and performance characteristics of significant heritage properties. Standard fire protection approaches, based on ideal (new construction) conditions that drastically differ from the conditions presented in historic buildings, can have adverse impacts on historic materials and spaces and destroy the very qualities that give a space its historic characteristics. These damaging approaches include removal of significant architectural features, and changes made for the installation of fire protection equipment. The problem is not in the introduction of these changes, but in their implementation without sensitivity and understanding of how each change affects the important aspects of the building. While building codes have progressed to keep up with developing techniques of modern construction, the issues of fire safety for heritage premises are relegated to guidance documents, e.g. [8, 6] , with no legal authority. A few rehabilitation codes have evolved that recognize the inherent differences between new construction and existing buildings, but they retain the inflexibility and additional problems of specification-based codes, and are inadequate in their approach to historic buildings, the subcategory of existing buildings with the highest requirement for property protection. None of the recent generation of codes has definitively resolved the conflict between the prescriptive language of fire safety and the philosophical language of agreements like the Venice Charters, documents used to identify appropriate preservation approaches and techniques.

In the early years of the twenty-first Century two important European research projects started on the issue "Fire and Historical Buildings". These two international research projects, FiRE TECH and Cost Action C17, represent the most recent and notable scientific works on the topic. This dissertation is based on the main concepts and procedures contained in those works. In the follow a resume of FiRE TECH and Action Cost C17 is given. Some previous important studies about fire risk were developed in Sweden, especially in Department of Fire Safety Engineering in Lund University, ref. paragraph 2.2.2.1. As widely explained, these studies produced risk analysis methods and techniques (FRIM-MAB) for fire managing in buildings (*note: not fire management in historical buildings*). Some fire safety engineering concepts from these studies are comprised in FiRE TECH report and are developed in this dissertation.

3.1 COST ACTION C17

The Action started in January 2001 and ended in December 2006; the work of COST Action C17 has been published as a series of Conference Proceedings [14, 18, 19, 20, 27] in support of a Final Report [86, 87, 88, 22]. The intention of the Action was to address the physical and significant cultural loss of Europe's built heritage to the damaging effects of fire. It was achieved in a multi-disciplinary, multi-national manner through the collaboration and integration of a variety of related projects. It was also based on research initiatives and published material resulting from a number of relevant international conferences. The outcomes were the promotion of data, methodologies, and management systems. The final aim was to assist a wide range of end-users balance fire engineering needs with conservation requirements in the future preservation of the European patrimony.

COST ACTION was conducted because, in addition to associated levels of life loss, the number, authenticity and quality of European historic buildings is being steadily eroded through the effects of fire. In 1983 this was recognized by the Council of Europe Committee of Ministers, who recommended "That the governments of the member states adopt all legislative, administrative, financial, educational and other appropriate measures to protect the built heritage from fire and other natural disasters". Therefore there was a need to find a balance between technological and management solutions to counter this disastrous effect of fire. The real scale of loss of historic buildings to fire was, and still partially is, unknown. Superficial data suggested that the annual and aggregated effect is considerable, perhaps as high as one important historic building each day. There was a general lack of statistical information, and a common lack of understanding and appreciation of what measures are available and required, to counter the effects of fire. Good guidance was urgently called for, on how to sensitively retrofit modern day equipment into historic fabric. There was also a need to develop related management expertise in the dealing with this problem in historic premises.

To assess the specific risks to a historic building requires the need to define possible, or expected, damage due to a particular hazard or phenomenon. There is a considerable number of historic buildings requiring protection. It is important to recognize that these historic buildings are a major contributor to the "sense of place" and they are of great importance to both inhabitants and tourists.

To be effective in historic building protection from fire, the need was to develop a high level of international co-ordination and strengthen the levels of trans-national multi-disciplinary co-operation. The need was to exchange and enhance experiences to increase awareness and understanding, and to focus future action. Networking partnerships were identified, their specialist input recognized and roles they perform classified. The associated skill and knowledge needed to be pooled, assessed and best practice developed. As said in the previous paragraph, several international conferences considered the topic of fire loss to the built heritage. But these did not provide the mechanism for encouraging and co-ordinating research projects. However, published proceedings offered an established understanding of the issues, although many of them remain unresolved in practical terms.

3.1.1 Objectives of the Action and Scientific Content

Across Europe the full extent of the physical loss of the built heritage to the effects of fire was unknown. Some suspect it was to be as high as one important historic building each day, but there were no reliable statistics upon which the real degree of destruction and cultural loss can easily be established. In integrating new technologies with traditional disciplines, there was a need to develop synergies within related organizations so that loss levels can be reduced and, ideally, halted. There was, therefore, an urgent need to integrate, co-ordinate, and assess the associated factors on a pan-European level so that a common state of the art understanding emerges to help combat such levels of loss. To address the problem a pan-European integrated approach was required. The operational framework considered the vulnerability of historic buildings to fire.

The final aim was to compile appropriate statistical information, including an analysis of expert opinion on the rate of loss of historic buildings to fire. The Action was based on the following concepts:

- To understand a common state-of-the-art and to appreciate appropriate countermeasures including concerted action to influence future developments in technology;

- To understand the financial protection of historic properties guidance on the sensitive integration and retrofitting of countermeasures;

- To promote statistical research into the consequences and causes of fires – both major fires and more minor incidences, (e.g. small fires to which the fire brigade are not called or false alarms) – and their impact;

- To use risk mapping data gathered as a basis for discussion, establishing a dialogue with insurance bodies to seek the development of insurance products more closely tailored to historic buildings;
- To establish a well-documented survey of technical expertise state of the art to assist in influencing future developments in fire protection technology for use in historic buildings;
- To define an appropriate range of passive and active technical equipment countermeasures;
- To consider alternative approaches to reduce current loss levels;
- To promote findings and benefits of relevant risk assessment methodologies and property management support.
- Results of the COST Action have to be targeted to building owners, property managers and conservation professionals to increase awareness and understanding.

3.1.2 Operational framework of the Action

To reach the Action objectives four working groups (WG) were created:
Working Group 1: Data, loss statistics and evaluating risks
Working Group 2: Available and developing technology
Working Group 3: Cultural and financial value
Working Group 4: Property management strategies
The operational framework of the Action was developed to consider the special nature of the value of historic buildings, the economic aspects of cultural historic value, and the need for measures to minimize damage if a fire occurs. Specifically this required consideration of the:

- vulnerability of historic buildings to fire
- risk assessment methodologies
- protection of fabric and content
- prevention of fire and fire spread
- detection and suppression requirements
- training and management of staff
- insurance considerations

In pursuing these intentions, there was a need to integrate and coordinate the associated factors so that a common understanding of the issues might emerge. To achieve meaningful results during the intended life-span of the programme, a strategic approach was adopted. Each WG produced a final report [18, 19, 20, 27].

3.1.3 Relevant results

The most relevant results from ACTION COST C17, interesting for this dissertation, are from Working Group 3 and Working Group 4. Working Group 1 in [98, 18, 71] and Working Group 2 in [19, 72] produced material that is in partial superposition with Fire Tech (ref. section 3.2) without having FiRE TECH's level of detail.

WG3 results: WG3 studied the "Cultural and financial value" issue employing judgments coming from experts and insurance companies [23, 121, 122, 123, 124, 125, 126, 24, 25, 26, 50].
Value for historical building is mainly linked to:

- costs for reconstruction (partial as well as total reconstructions will be carried through with the same material and the same construction as the original to the greatest possible extent, with regards also to economy);
- economic value;
- cultural value.

The definitions from the different countries in Europe seem to correspond very well. Still different traditions give different emphasis on different aspects and slightly different expressions in their definitions. From [23, 123] the following are the main criteria of cultural historic value:

- historic interest, that includes buildings which illustrate important aspects of social, economic, scientific, cultural (literature, theatre, film, art, architecture etc) or military history -architectural interest, which means buildings of interest for their architectural design, decoration and craftmanship;
- technical interest, which means buildings of interest because of technical innovations. This issue is in many countries included in architectural interest;
- group value, where buildings are important as part of an interesting or beautiful unity.

Enhancing factors or added value can be:

1. authenticity or genuineness
2. representativity or rareness, if the building is very typical or very special
3. clarity and educational potential, if the building is suitable for presenting or displaying its history and other values as education or for tourists
4. the degree of importance; is it important for a village, for a town, for a region, for a country or for mankind

Aspects also to take into account are:

1. quality or state of maintenance

2. usefulness/functionality

From report [127]:

> *"Cultural historic value is invaluable and priceless. Cultural historic valuable buildings are not replaceable and sometimes they have not got a market. That does not mean that they have not got an economic value. Usually they have an important economic value for society also if they don't have an economic value for the owner. It is important to understand that especially in discussions about the costs for fire prevention measures to take and for insurance. Today in most countries it is impossible to get grants for fire prevention also in listed buildings of great importance. That has to be changed."*

From one point of view it is impossible to calculate and set an economic price on the cultural historical value of a building. On the other hand it is too dangerous not to set a price on the cultural historic value of a building of great cultural historic value. It is easy to forget that something priceless costs a lot to protect and is extremely difficult and expensive to recreate even the fabric of such a building. In summary it is established in [127] that the economic value of a cultural historic building consist of the value for the:

- owner in terms of market value;
- tourist industry;
- enterprise who can use the value in different ways;
- society.

WG4 results: WG4 studied the "Property management strategies" issue and it is the most effective result of ACTION COST C17 [73, 42, 17]. In WG4 final report there is the real core of Action's recommendations. The report is in fact directly addressed to the building managers and states the best practice to manage protection and prevention in historical heritage buildings.

The WG4 final report [27] dealing with property management strategies, contains documentation encompassing the whole range of management regimes for risk preparedness as well as staff training, audit and controls. The WG4 considers that the management of fire risks is as important as technical improvements to historic buildings and the on-going need risk assessment. Using the risk management approach, all three facets - risk assessment, management and technical solutions - form an integral part of the property management process.
The perspective of a performance-based approach in planning risk assessment and upgrading buildings and strategies is the answer to the possible conflict between life safety and historic object fire improvement.

3.2 FiRE TECH: Fire Risk Evaluation To European Cultural Heritage

FiRE TECH started from the consideration that fire protection of cultural heritage has had no high priority in the fire safety business. The resources available for protection of cultural heritage against destruction by fire were, and still often are, limited and insufficient for the perceived needs. Authorities - European, national and local - had to select the projects on an intuitive basis, as there is no technical guidance available. Furthermore, authorities in charge of the protection of cultural heritage found no support in prescriptive national fire safety regulations: there is a lack of well-found methods allowing a correct evaluation of the fire risk incurred by cultural heritage and the tools needed to estimate the efficiency of different fire protection measures for building and contents are still missing.

3.2.1 Scientific objectives and approach

FiRE TECH first scientific objective is the development of an evaluation tool taking into account all the parameters expected to influence decisions when prioritising fire protection projects in cultural heritage. This goal includes the elaboration of quantitative methods or the adaptation of existing ones for the evaluation of the different parameters/criteria intervening in the decision process. These parameters are the fire-risk, the efficiency of the measures and their cost.

In parallel with the first scientific objective, the second objective is to give an overview and examine the relative benefits and drawbacks of the various components of fire safety techniques. This means a comparison between the different possible strategies of protection, identification of the weaknesses of the existing techniques and the proposal of alternative solutions. Usual fire protection techniques are often not applicable and/or not acceptable for the protection of cultural heritage. There is an important lack of specific information on fire safety technology for cultural heritage.

Under this project, an evaluation tool is to assist authorities in prioritising fire protection projects and selecting projects on the basis of objective criteria. These take into account all the selected criteria/aspects in order to optimise the use of the available financial resources by the selection of those projects providing the highest gain for the investment made.

The innovative aspect of the project is that the problem of “fire protection of a cultural heritage” is in FiRE TECH approached from the viewpoint of 'Fire Safety Engineering'.

3.2.2 Operational framework of FiRE TECH

To reach the objectives of the research, eight working groups (WG) were created:
Working group 1: Identification of the existing practices and regulations and the motivation behind them
Working group 2: Analysis of fires involving cultural heritage
Working group 3: Fire performance of ancient materials
Working group 4: Existing fire safety technologies and products

Working group 6: Risk Analysis
Working group 7: Development of a quantitative decision model/method
Working group 8: Case Studies
Working group 9: Database

Each group was composed of academics coming from different European Universities and, at the end of the research, some technical reports and a final report for each group was published [62, 115, 54, 21, 84, 91, 41, 15, 49, 116, 1]. Additionally a guide was developed describing the use of fire safety engineering approaches to protect cultural heritage. The information is made available to all interested parties by the publication of a guidance document under book format [117].

3.2.3 FiRE TECH methodology

FiRE TECH methodology in analysing Historical Heritage Buildings under fire is structured in five main parts described in this paragraph. In Figure 3.1 a diagram representing the method is shown .

3.2.3.1 Agree the objectives – STEP 1

At first, we need to establish the main goals of the analysis. Usually the objectives are:

- OB1 - to protect the occupants
- OB2 - to protect the firemen
- OB3 - to protect the building
- OB4 - to protect the contents
- OB5 - to safeguard the continuity of activity
- OB6 - to protect the environment

For cultural heritage buildings the particular intention of protecting the building and/or the content may be as important as - or even more important than - the protection of people or firemen. For cultural heritage buildings in old urban areas, the protection of neighbour buildings (OB6) may become equally important or even more important than the protection of people. It is requested to evaluate these objectives, ranking them in order to decide the most urgent priority. At this step there is the definition of acceptance criteria: they are an expression of the opinion of the stakeholders on the expected/required level of satisfaction for each of the objectives. An acceptance criterion for the protection of cultural heritage buildings and content may be a limit for loss (in percentage or in money unit). An acceptance criterion for the protection of people may be, for examples, "total evacuation in 5 minutes" after detection of the fire.

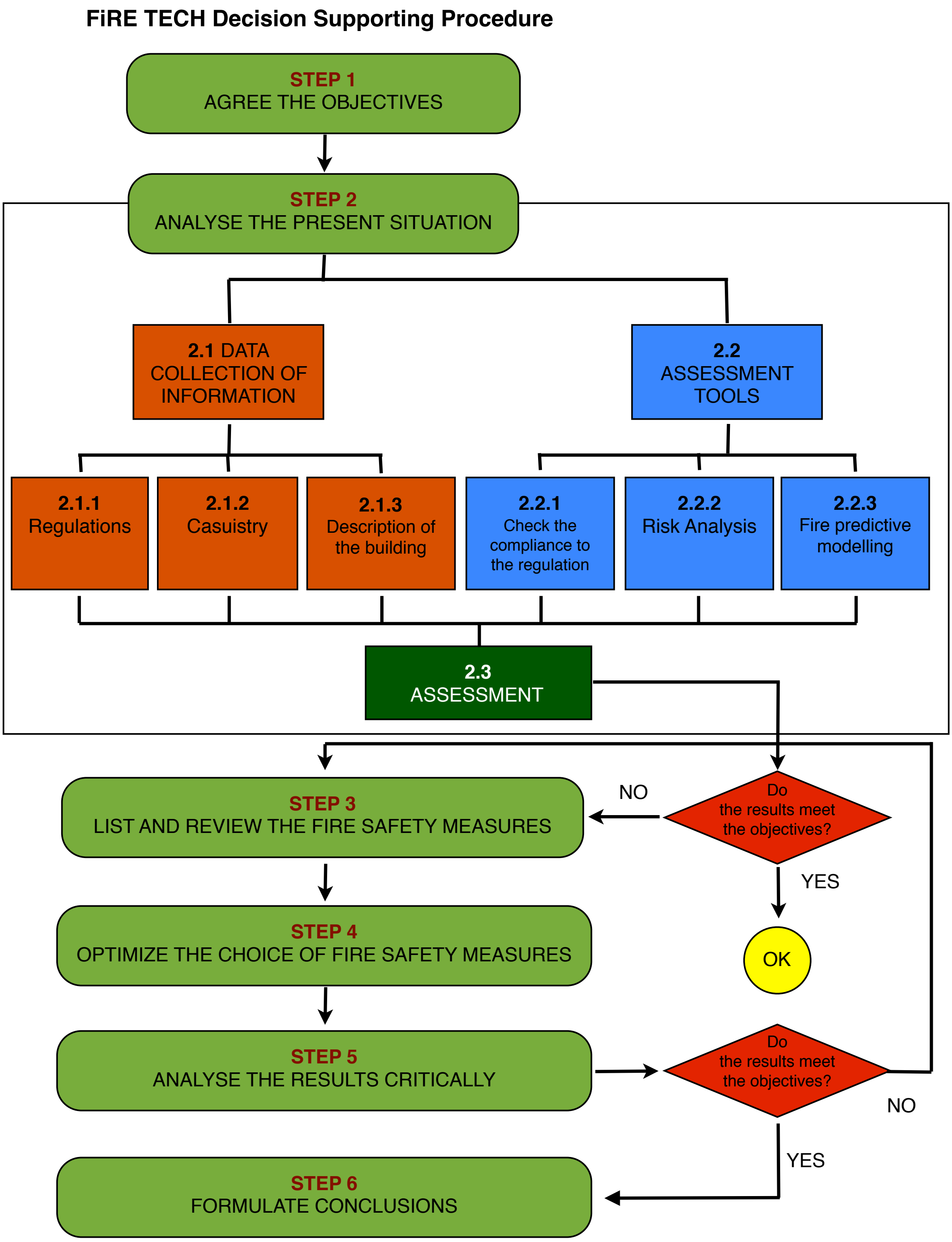


Figure 3.1: Diagram of FiRE TECH procedure, an elaboration from [117].

3.2.3.2 Analyse the present situation - STEP 2

This step is divided into two main parts: data collection of information and assessment tools review.

Data collection of information - STEP 2.1 It consists of three main parts described in the follow.

Collection of fire safety regulatory elements - STEP 2.1.1 Collect all the regulations applicable to the cultural heritage building studied. In addition to general national regulations it is necessary to pay attention to local regulations, to particular regulations for cultural heritage buildings and to particular regulations for the intended use of the building.

Information out of previous fires occurred in cultural heritage buildings - STEP 2.1.2 Information from previous fires allows the identification of:

- the most common causes of fire in cultural heritage buildings,
- typical fire development in cultural heritage buildings
- potential fire safety measures

In general most common causes appear to be arson, deficient electric circuits and renovation works.

Description of the building - STEP 2.1.3 A complete description of the building, including all elements that may have any influence on fire safety/fire prevention has to be produced. This includes the following elements:

- <u>Concept and fabric of the building</u>
  It's a description of the configuration of the building, of the layout, of the geometrical characteristics of the building. We have then to individuate all the different zones in the building: circulation paths, exits and potential evacuation routes, rooms for particular activities, fire compartment if they exists. It's also a description of the materials constituting the fabric of the building (with special attention to those elements which are important for the evaluation of the resistance to fire of structural and separating elements) and the reaction to fire of wall, ceiling and floor coverings.
- <u>Content/fire load of the building</u>
  Consists of an estimation of the immobile fire load and an estimation of the expected mobile fire load. This information allows an estimation of the potential fire duration.
- <u>Technical installation</u>
  These technical installations need to be described in terms of their condition, the number, the type, the maintenance, the control of the installations and fire safety provisions.

- Function/use of the building
  Here a detailed description is required: the function/use needs to be defined for the different areas (or compartment if they exist).

- Type of the occupants of the building
  Report whether the building has day time or night occupancy. Define the typology of occupants (familiar/not familiar with the building, mobile independent/mobile dependent persons, age of persons).

- Description of the history and value of the building and its contents
  The architectural and structural changes during the different renovations are of interest for the fire safety of the building. It may be necessary to split the building into specific sections (facades, specific rooms or wings...) and content (special objects who might need extra protection).

Assessment of the present level of safety - STEP 2.2 For the present level of safety assessment three approaches are available:

- Regulations and check lists - STEP 2.2.1
  It may be assumed that a satisfactory level of safety will be achieved by applying the existing building codes, where this is possible. They have very little to do with risk assessment methods but give a straight forward way of providing fire safety. A number of detailed rules have to be followed and no "real" risk analysis is carried out. Regulations and check lists do not quantify the risk.

- Evaluation of fire risk with risk assessment tools - STEP 2.2.2
  A fire risk analysis for the existing situation has to be carried out. In FiRE TECH a quantitative method has been chosen.

- Assessment of fire risk via fire predictive modelling - STEP 2.2.3
  This kind of assessment implies the use of computer simulation models. Many fire development models are available for the calculation of temperature evolution, smoke spread etc... (zone models, Computational Fluid Dynamics Models), for the calculation of structural behaviour, evacuation models for the modelling of human behaviour during escape.

Risk assessment method used in FiRE TECH - STEP 2.3 FiRE TECH method for risk assessment is based on the risk definition

$$R = P \cdot D \tag{3.1}$$

with P the happening probability of an event and D the damage associated with that event (ref. 2.1). Event Tree Analysis is used to define probabilities for each risk scenario while fire spread models are used to define damages.

ETA is a binary system with a logical graphic presentation. The event tree procedure consists of the following steps:

1. selection of the events;
2. event tree design;
3. quantification of fire development;
4. assessment of damage;
5. calculation of risk measures;
6. risk evaluation.

The risk analysis itself is carried out by quantitatively evaluating a number of fire scenarios. The evaluation calculates the fire development and the evacuation process for all scenarios in the event tree. Event trees are logic diagrams, which can be used to illustrate the sequence of events involved in ignition, fire development and control, as well as the course of escape. The risk for each scenario is calculated by multiplying the probabilities for the specific scenario. The total probability for a given outcome to occur is the sum of all specific probabilities for a given scenario. The total risk associated with a building is the sum of the risks for all scenarios in the event tree.

Selection of the events - STEP 2.3.1 Events included in a life safety analysis are related to the fire development itself and to the possibility of a successful escape. The first event of the event sequence is called the starting event. Depending on the occurrence of one or more intermediate events, different outcomes can occur. The initiating event in fire risk analysis is most commonly "initial fire". In the following some events related to the fire event are listed:

- fire location
- source of ignition and first item ignited
- possibility of early suppression by staff
- presence of an automatic suppression system
- smoke ventilation.

Events related to successful escape:

- number of people in the building
- operability of fire detection
- operability of notification system
- number of escape exits available

Events related to the spread of fire and fire gases:

- spread through heating, ventilation and air conditioning systems

- open doors
- unsealed openings between fire compartments.

In order to find proper reliability data for the included events, the engineer could rely upon data banks, engineering judgment and sometimes other frequency modelling techniques as fault trees. In FiRE TECH the probability of having a fire in either of the locations is related only to the floor surface dimension.

Event tree design - STEP 2.3.2 The objective of an event tree is to provide insight into the possible consequences of one initiating event (e.g. a fire). The selected events are brought together in the event tree. The events must come in the order they physically take after a fire. In each branch, the conditional probability of the included events is calculated. The probability data for each event derive both from statistical researches and from engineer judgment about the analysed situation.

Quantification of fire development - STEP 2.3.3 The fire development is quantified by the use of suitable methods. These could either be more simple calculation methods or more advanced computer simulations. The aim of quantifying the fire development is to derive information on how certain fire-related parameters vary with time (such parameters could be smoke layer height, temperature, visibility level, radiation, concentration of soot and toxic species, etc...). This information could be made available by the use of hand calculation equations for more simple structures and by the use of CFD (Computational Fluid Dynamic) models for more complex buildings. Hand calculation equations are used to evaluate the flame spread rate and to assess radiation levels to walls and ceilings as the fire develops. Graphics about the fire development are drawn regarding the fire growth (measured in squared meters) over time.

Assessment of damage - STEP 2.3.4 The damage to the building is assessed for all scenarios in the event tree. The state function, to assess if damage will occur or not, is the following:

$$t_{unt} \geq t_{esc}, t_{sup} \tag{3.2}$$

where:

$$t_{unt} = \text{time to reach untenable conditions} \tag{3.3}$$

$$t_{esc} = \text{time to complete escape} \tag{3.4}$$

$$t_{sup} = \text{time to suppression} \tag{3.5}$$

Considering the safety of people, the negative difference in the state function could be used to asses the number of people who will not have the possibility to conduct successful escape. When addressing property protection, the state function could be used to assess the fire damage area. For each scenario we have to be able to assign a time of realization. With such a data we can quantify the damage entering in fire development graphs (pt. 2.3.3 above) and deriving the damaged surface D.

Calculation of risk - STEP 2.3.5 When the fire development and the fire damage have been assessed for all scenarios in the event tree, it is possible to derive certain risk measures.
Given the happening probability for each one of the ETA branch, with some calculation we obtain the happening probability for each scenario.

Then "outcome" is defined as the set of scenarios with the same time of realization and consequences. It is possible to calculate the happening probability for each outcome.

After calculating damage with the method expressed above in 2.3.4 and having the happening probability for each outcome, it is possible to assign a Risk Average to each outcome.

3.2.3.3 Review the possible fire safety measures - STEP 3

The aim of this step is to list the possible fire safety measures for the case studied, to consider their individual acceptability and reliability, and to provide the information required for the application of the optimisation methods as applied under step 4. This includes an estimation of the cost of each possible measure. The evaluation of the criteria acceptability, system reliability and cost has to be carried out for the specific case study and will differ from case to case.

POSSIBLE MEASURES
Possible measures are listed in FiRE TECH:

1. Reaction to fire
2. Fire resistance of structure
3. Fire resistance of partitions
4. Size of fire compartments
5. Characteristic and location of openings on the facade
6. Distance between buildings
7. Geometry of egress paths
8. Access for the firemen
9. Means for fire detection
10. Means for fire suppression
11. Smoke control
12. Emergency and alarm signs
13. On-site firemen
14. Fire brigades

15. Maintenance of fire safety systems
16. Education for fire safety
17. Emergency planning and training
18. Salvage operation management
19. Periodic inspection of the building

EVALUATION CRITERIA

The evaluation criteria are mainly three:

1. Acceptability
   The acceptability of systems means whether the system/product is suitable for the use in cultural heritage buildings. Acceptability will depend on criteria which have to be established by the stakeholders and usually depends on architectural or urban criteria and on conservation criteria.
2. System reliability
   The reliability of a system can be defined as the likelihood that the system will exhibit the desired response in the event of a fire occurring, and can be expressed either quantitatively or qualitatively, provided that sufficient statistical data are available.
3. Cost
   The costs to be considered include:
   - capital cost
   - manpower/installation cost
   - annual running cost
   - maintenance cost
   - replacement cost

3.2.3.4 Optimize the choice of fire safety measures - STEP 4

In this step a mathematical technique is applied in order to select the most efficient and cost-effective fire protection measures, using the information collected in the previous steps. The method proposed in FiRE TECH is the Analytical Hierarchical Process (AHP). AHP is a practical technique for modelling and solving multi-criteria decision problems. The AHP-approach facilitates the development of logical hierarchical structures for complex decisions. A logical framework is set up, which allows improving the performance of complex decisions by decomposing the problem in a particular hierarchical structure. The incorporation of all the decision criteria allows the decision-maker to determine trade-offs among objectives. The application of the method exploits two kinds of knowledge in the process of priority, setting when to conceive the “boxes” of the network as well as when to decide weights relative importance:

- information gained from the expertise/knowledge of the participants;
- measured or calculated information.

3.2.3.5 Analyse the results critically - STEP 5

In this step the results are reviewed critically with all stakeholders and it is checked whether the results correspond to everyone's expectations or not. It is verified whether the proposed measures after all:

1. satisfy the predefined boundary conditions;
2. meet the safety level required in the existing regulation;
3. correspond to the existing/common practice;
4. are logical.

This check is to be done with the same assessment methods as used in step 2 (checklists, risk analysis methods, fire predictive methods). If the results are not satisfactory the steps 3 and 4 need to be reviewed. The optimisation process has to be checked on errors, inconsistencies, contradictions. If nothing of abnormal is found, the process from step 3 needs to be repeated with extra measures.

3.2.3.6 Formulate conclusions - STEP 6

Finally it is necessary to formulate the conclusion for the stakeholders, to propose measures to be taken, to give advise on the order of cost/effectiveness on the proposed measures, to give advise on their estimated costs and reliability, to include the demonstration of the improvement of fire risk.

3.3 COST ACTION C17 and FiRE TECH: relationships

Both FiRE TECH and COST C17 start from the consciousness raising about the need to establish common European strategies in fire fighting for historical buildings and contents. Despite the common basis and organization in Working Groups, the two researches have different scientific objectives and different addresses.
FiRE TECH panel of members was primarily composed by academics working in Fire Safety Engineering and produced results (*in primis* the "decision supporting procedure" ref. 3.2.3) mainly useful for academic people.
ActionCOST C17 panel of members was composed by people involved from various angles in heritage preservation and protection (heritage cultural officials, museum managers and owners, fire brigades, heritage building's safety managers) and produced recommendations useful both for building's managers and owners.

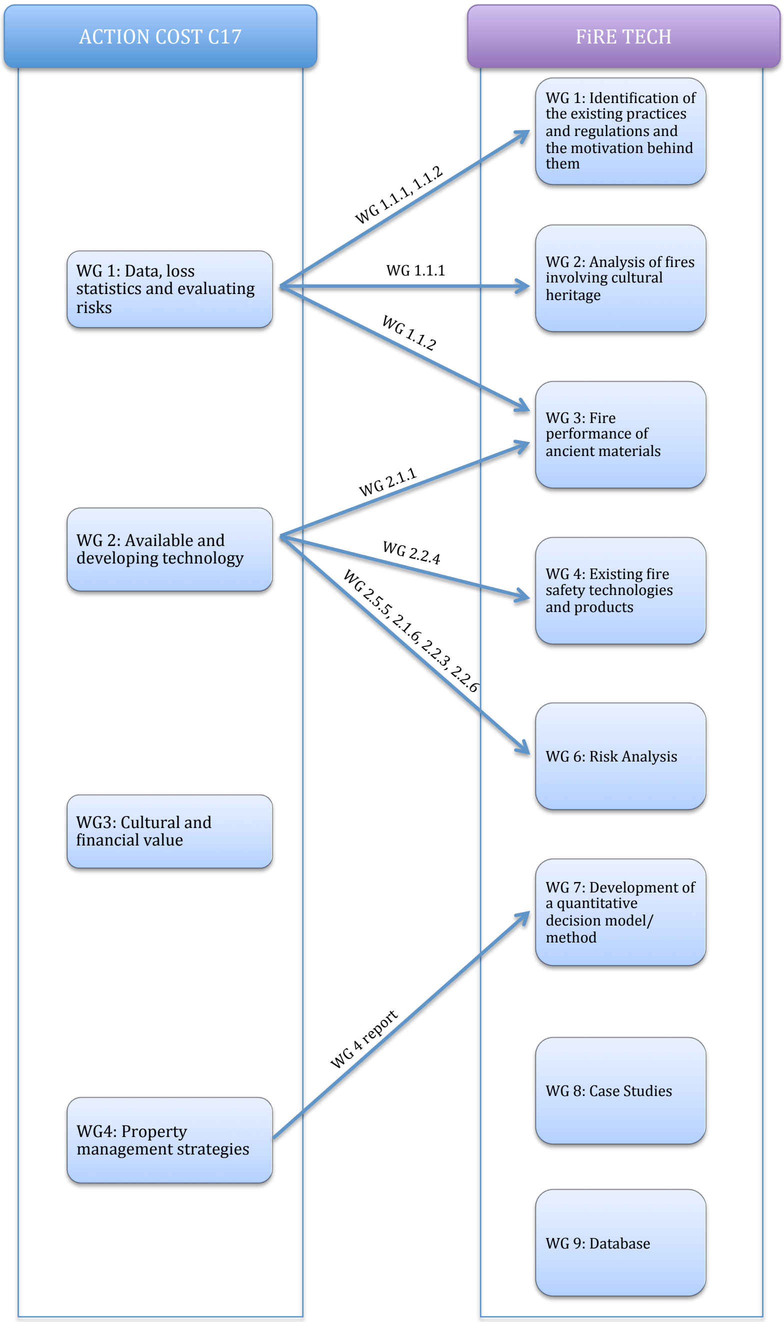


Figure 3.2: Relationships between FiRE TECH and COST C17.
Arrows link COST Working Group dealing with similar topics of FiRE TECH WGs.
On the arrows report's references are depicted.

From paragraphs 3.1 and 3.2 it is possible to understand how much superposition and mismatches there are between the two researches, see fig. 3.2.

With the attempt to overcome such mismatches and superpositions, in this dissertation a procedure to improve standard level of fire safety for contents is proposed.

Chapter 4

Risk Management Procedure

4.1 Objective of the Procedure

This dissertation has the goal to provide a *risk management procedure* in order to improve fire protection of Valuable Contents contained in Historical Heritage Buildings. It is here proposed the *Risk Management Procedure for Valuable Contents in Historical Heritage Buildings.*

The procedure has been built using some of the concepts from FiRE TECH's decision supporting procedure, with the aim to respect COST C17 recommendations in managing contents and preventing losses due to fire events.

According to Action COST C17 scientific mission [87], guidance should be provided to owners of properties and managers on developing management plans for their properties to include areas such as *Damage Limitation and Liasons with the fire service.* The managers of historical buildings have to be surrounded by specialists who can advise them and provide the information from which to gain a full understanding of the risks associated with the historic building.
This should address:

- appropriate risk management principles;
- the need of protection;
- realistic valuation of reconstruction costs for heritage buildings (comprised in losses estimation).

As stated in [86], all those engaged in protection of valuable cultural heritage should pay attention to:

- the protection (or lack of protection) of valuable cultural historic buildings and contents;
- appropriate insurance cover, that is linked to building and contents risk assessment.

COST C17 recommends, in addition, that special circumstances regarding historic buildings must be described and analysed in the risk analysis:

- the special vulnerability of the building;
- the activities in the building;
- its fabric and its structural features;
- its surroundings or activities in the surroundings;
- the probability of ignition;
- the distance to the fire brigade.

As shown in section 4.3, most of this features are comprised in the proposed procedure, which has the aim to be an "easy-to-use" screening tool helping in Valuable Contents fire risk management. *Risk Management Procedure for Valuable Contents in Historical Heritage Buildings* is a decision procedure built according to COST C17 recommendations.

4.2 Starting Hypothesis and Addressees of the Procedure

Each Historical Heritage Building in Italy, open to the public and containing precious Works of Art (ref. chapter 1, section 1.3 for definitions), is supposed to be "safe" with respect to fire protection, according to national codes. The main objective of the Italian fire protection codes is *safety of the occupants.*

Ways technicians can use to reach the objective of safety for occupants and the chosen one are building dependent. To this day, Performance Based Design in fire protection is allowed in Italy thanks to D.M. 09/05/07 [28]. Fire Safety Engineering concepts can be used as well as standard codes application to demonstrate building's safety; this usually happens when prescriptive codes alone cannot be applied. Historical Heritage Buildings are a pertinent example of such situations and FiRE TECH is the only example of "decision procedure" in fire prevention that involves, together with safety of the occupants, safety of the building and of the contents.

In this dissertation we want to illustrate a different and more specific procedure that is able to improve standard level of fire safety in Historical Heritage Buildings, addressing the interest mainly to contents protection.

It is made therefore the assumption that the building we are going to study reaches the basic level of fire protection for occupants, according to Italian law and codes. Obviously there is a link between the building and its contents; in particular, dealing with valuable contents and works of art, in a lot of situations such items are integral part of the fabric itself. We are mainly interested in *"mobile contents"* (wooden and textile pictures, statues, jewels, some kind of furniture, porcelains, etc.) because of the possibility to intervene with contents evacuation actions. On the other side we can not neglect the *"not mobile contents"* (frescos, heavy statues, heavy furniture, tapestries, etc.) but such items are usually intrinsically protected by the standard fire protection intervention that we consider to be effective. In spite of all, all the possible link between building and contents protection are considered in the procedure, so that risk mitigation for *"mobile contents"* imply necessarily an improvement of protection also for *"not mobile contents"*.

More in detail, Historical Heritage Building's Managers (ref. chapter 1, section 1.3 for definitions) have by law the duty to protect from fire:

- building;
- people inside building;
- contents.

As widely said, nowadays protecting the occupants is the primary duty requested from Italian laws on safety. Usually fire protection interventions on historical building are made respecting the building characteristics and trying to protect also the building, as far as the intervention is compatible with the architectonic configuration.We assume, this way, that the first two duties are usually discharged adopting a fire safety design according to codes. Anyway, none specific italian code or law have the building and content protection as its primary goal. Managers have however responsibility for the Valuable Contents inside the building but in Italy (and in other countries as well), there is no specific law addressing to the contents preservation from fire in terms nor prescriptive or performance based. The only instrument now available to manage content protection from fire is the COST C17 set of recommendations.

We want here to define a screening instruments suitable for Historical Heritage Buildings' Manager. As the addressee of the COST recommendations is the Manager of Historical Heritage Building, he is also the addressee of the *Risk Management Procedure for Valuable Contents in Historical Heritage Buildings*.

4.3 Structure of the Procedure

The core of the procedure is structured in two main parts:

1. Risk Assessment;
2. Risk Treatment.

The fundamental relationships among the two parts are shown in figure 4.1.

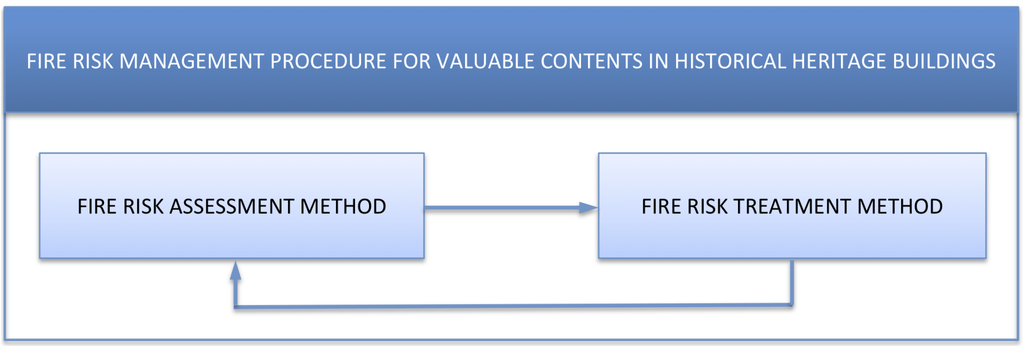


Figure 4.1: Conceptualisation of the relationships among Risk Assessment and Risk Treatment.

At the top of the procedure there is a phase dedicated to the building's analysis and data collection (not represented in figure 4.1), refer to section 4.3.1. This preliminary step has the duty to provide to users all the necessary information to run the procedure correctly. This first screening can be done using check lists, as suggested in Annex A.

All the collected data are the inputs for the Risk Assessment phase that produces, as output, risk indexes concerning control parameters; refer to section 5.1.4 in chapter 5. Risk Treatment phase has now to be performed in order accept or not accept and mitigate the results from the first phase. If it is necessary to intervene with some actions of mitigation, the Risk Assessment phase has to be conducted again to evaluate the efficacy of the actions.

In Figure 4.2 the full structure of *Risk Management Procedure for Valuable Contents in Historical Heritage Buildings* is depicted.

4.3.1 Building analysis and data collection

This preliminary phase is introduced to make *Risk Management Procedure for Valuable Contents in Historical Heritage Buildings* work in terms of slenderness. First aim is to approach historical building's analysis without the necessity to collect the big amount of complex data required e.s. from FiRE TECH. The preliminary phase should be able to direct the decision maker to focus and analyse in depth only the most critical building's features. Sometimes high complexity due to architectonical features and miscellaneous use of the building is quite difficult to be fitted. By means of the preliminary phase, we want to become confident with the building and to exclude from full analysis procedure the less interesting areas.

Since there is the necessity to have the maximum reduction of input data, we refer to the most easily detectable information. In gathering information, we refer to two groups of data: the external and the internal ones. Each elementary information to be gathered is related to "Sub-Factors" [ref. chapter 5 section 5.1.6] and all the required information can be deducted from:

- study of the building's plans and sections;
- study of historical and architectonical development of the fabric;
- simple survey of technical installations;
- collection of data linked to the occupants and the use of the building;
- urban analysis of the building's context;
- at least one physical inspection to the building.

Information useful for the procedure are divided into two different sets: external data and internal data. External data set is just one for each building while internal data sets are usually more than one for each building, depending on the complexity of the fabric.

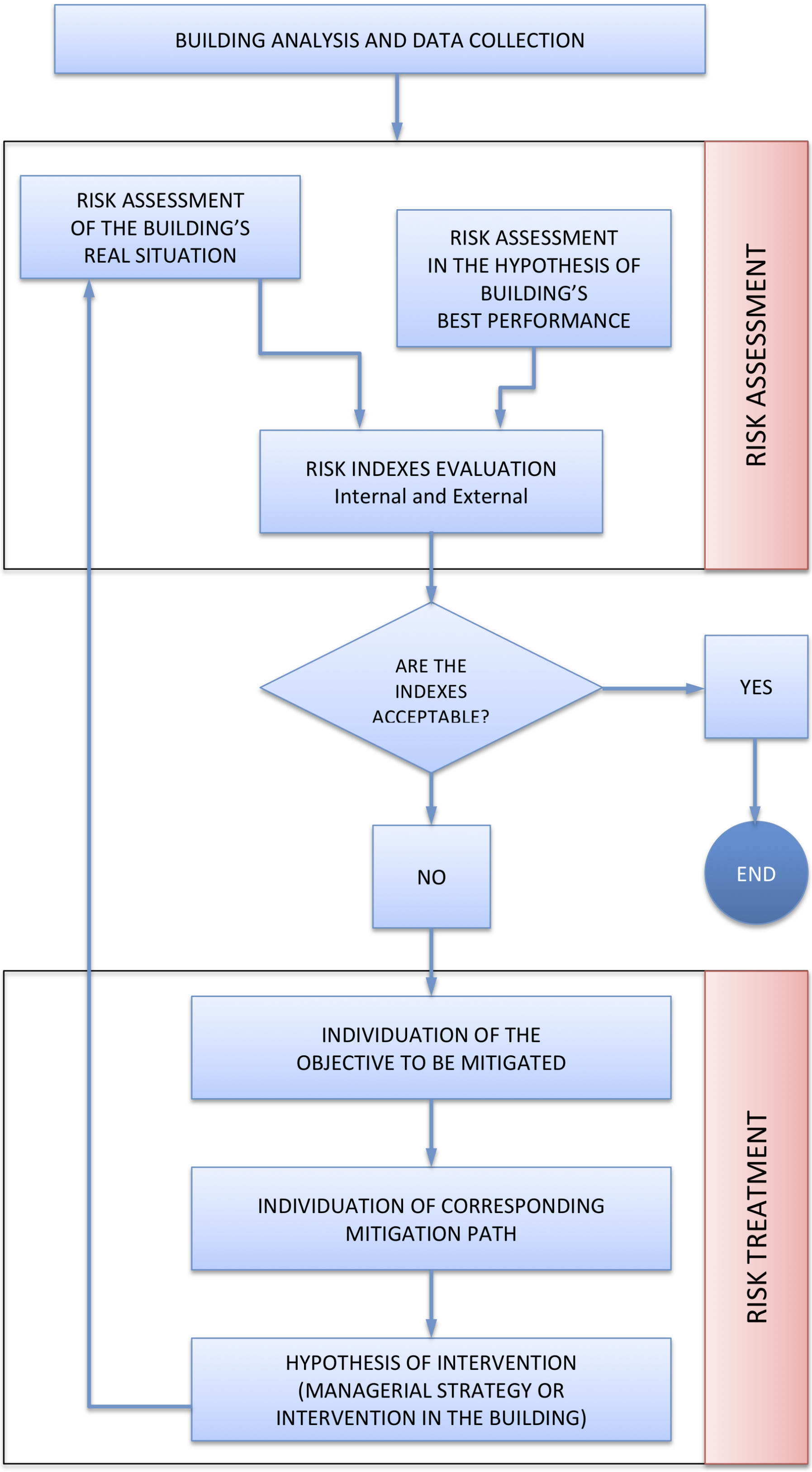


Figure 4.2: Representation of the *Risk Management Procedure for Valuable Contents in Historical Heritage Buildings* structure.

External Data
The external data consist in the collection of all the architectonical features that can be attributed to the building itself from a macroscopic view; all the external data are not variant inside the same building. Such analysis is also introduced to relate the city context of the building to its behaviour in fire event. Especially in Italy, urban context could be the first weak point in historical building's fire protection.

Internal Data
Each internal data set comprehends all the building's technical and architectonical features that are variant in the building. So, in gathering data from an internal point of view, we need at first to individuate which are the building's sectors that have to be catalogued. This choice could be done according to the definition of *Sector* based upon one (or some) of the following criteria. A *Sector* could be individuate as:

- part of the building with the same destination of use;
- part of the building that is a single architectonical unit (a building's level, a single special room - a theatre, an hall, a double-height salon, a series of rooms with common features);
- part of the building that is a fire compartment (with respect to the regulation definition).

4.3.2 Risk Assessment

In Risk Assessment phase, a risk analysis and evaluation method developed on the base of FiRE TECH and FRIM MAB is used. The proposed procedure is based on FiRE TECH way of applying concepts belonging to Fire Safety Engineering to historical buildings. Getting ideas from FiRE TECH's STEP 4 [ref. paragraph 3.2.3.4 in chapter 3]; according to [74], a Analytical Hierarchy Process technique has been identified among the existing semi-quantitative risk methods, ref. chapter 5 section 5.1. This choice has been done also according to Cost Action C17, that in [23] recommends that:

> *"Analytic methods based on logical systems instead of using statistics (i.e. fault tree and event tree analysis) to be used for separate buildings or small and big establishment."*

In Risk Assessment phase we want to point out which are the weak points in contents' protection due both to building features and to management strategies. To feed the Hierarchy Structure with reliable data, experts' judgments have been collected making use of a Delphi Method performed in Italy, ref. section 5.2 in chapter 5. The expert panel for this research has been selected among Italian academics, fire brigades and technicians involved in historical building's management. The tool is therefore calibrated on the Italian situation, especially the Tuscany one.

Risk Assessment phase is described in chapter 5.

4.3.3 Risk Treatment

After a detailed risk analysis performed with the method described above, it is then proposed a strategy to chose the best set of mitigation measures in order to reduce the risk for Valuable Contents. In this phase it could be possible for the manager (with the support of the building technicians) to accomplish a set of measures able to mitigate fire risk for contents.
Risk Treatment phase is described in chapter 6.

Chapter 5

Risk Assessment Method

5.1 Analytical Hierarchy Process

The Analytic Hierarchy Process (AHP) is a multi-criteria decision-making approach and was introduced by Thomas Saaty for the first time in 1977 and then re-elaborated [103, 104, 102, 105]. Multi-criteria decision-making (MCDM) plays a critical role in many real life problems and several methods have been proposed for solving multi-attribute decision making problems [130, 39]. Very often these criteria conflict with each other. Even more often the pertinent data are very expensive to collect, nevertheless AHP is a method that is widely used in a lot of engineering applications [111, 57, 39].

We need to organize problems in complex structures which allow us to think about them one or two at a time. As stated by Saaty [104], we need *simplicity* and *complexity*. We need an approach that is conceptually simple so that we can use it easily. And at the same time, we need an approach that is robust enough to handle real world decisions and complexities.

The Analytic Hierarchy Process is such a problem-solving framework. It is a systematic procedure for representing the elements of any problem. It organizes the basic rationality by breaking a problem down into its smaller constituent parts and then calls for only simple pairwise comparison judgments to develop priorities in each hierarchy.

The AHP concept stems from the following three principles for explicit logical analysis:

- Hierarchy representation and decomposition: breaking down the problem into separate elements;
- Priority discrimination and synthesis: ranking the elements by relative importance;
- Logical consistency: ensuring that elements are grouped logically and ranked consistently according to a logical criterion.

The first principle of AHP concept involves construction of a functional hierarchy to decompose complex systems into their constituent parts according to their essential relationships. The elements in the hierarchy compose a cluster of system objectives, decision criteria and the attributes of criteria. Each set of elements in a functional hierarchy occupies a level of the hierarchy [46].

From an operative point of view, according to Saaty [105], in order to make a decision in an organised way to generate priorities, we need to decompose the decision into the following steps:

1. Define the problem and determine the kind of knowledge sought;

2. Structure the decision hierarchy from the top with the goal of the decision, then the objectives from a broad perspective, through the intermediate levels (criteria on which subsequent elements depend) to the lowest level (which usually is a set of the alternatives).

3. Construct a set of pairwise comparison matrices. Each element in an upper level is used to compare the elements in the level immediately below with respect to it.

4. Use the priorities obtained from the comparisons to weigh the priorities in the level immediately below. Do this for every element. Then for each element in the level below add its weighed values and obtain its overall or global priority. Continue this process of weighing and adding until the final priorities of the alternatives in the lower level are obtained.

To make comparisons, we need a scale of numbers that indicates how many times more important or dominant one element is over another element with respect to the criterion or property with respect to which they are compared. In this dissertation we will refer to the scale proposed by Saaty, Tab. 5.1.

Intensity of importance	*Definition*	*Explanation*
1	Equal importance	Two elements contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favour one element over another
4	Moderate plus	
5	Strong Importance	Experience and judgment strongly favour one element over another
6	Strong plus	
7	Very strong or demonstrated importance	One element is favored very strongly over another, its dominance is demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one element over another is of the highest possible order of affirmation
1.1-1.9	If the activities are very close	It may be difficult to assign the best value but when compared with other contrasting activities, the size of the small numbers would not be too noticeable, yet they can still indicate the relative importance of the activities

Table 5.1: Scale of importance proposed by Saaty, [103, 104, 102, 105].

AHP is a useful technique for discriminating between competing options in the light of a range of objectives to be met. The calculations are not complex and based on simple mathematical techniques.

5.1.1 Analytical Hierarchy Process theory

The mathematical basis of the AHP can be explained in fairly simple outline. For a full treatment of the AHP the mathematically undaunted should refer to Saaty's articles [103, 104].

The AHP has four axioms, (*i*) reciprocal judgments, (*ii*) homogeneous elements, (*iii*) hierarchic or feedback dependent structure, and (*iv*) rank order expectations.

Assume that one is given n stones, $A_1, ..., A_n$, with known weights $w_1, ..., w_n$, respectively, and suppose that a matrix of pairwise ratios is formed whose rows give the ratios of the weights of each stone with respect to all others. Thus one has the equation:

$$Aw = \begin{array}{c c} & \begin{array}{ccc} A_1 & \dots & A_n \end{array} \\ \begin{array}{c} A_1 \\ \vdots \\ A_n \end{array} & \begin{pmatrix} \frac{w_1}{w_1} & \dots & \frac{w_1}{w_n} \\ \vdots & & \vdots \\ \frac{w_n}{w_1} & \dots & \frac{w_n}{w_n} \end{pmatrix} \end{array} \cdot \begin{pmatrix} w_1 \\ \vdots \\ w_n \end{pmatrix} = n \cdot \begin{pmatrix} w_1 \\ \vdots \\ w_n \end{pmatrix} = nw \tag{5.1}$$

where $\mathbf{A}$ has been multiplied on the right by the vector of weights w. The result of this multiplication is nw.

Thus, to recover the scale from the matrix of ratios, one must solve the problem $\mathbf{Aw} = \mathbf{nw}$ or $(\mathbf{A} - n\mathbf{I})\mathbf{w} = 0$. This is a system of homogeneous linear equations. It has a nontrivial solution if and only if the determinant of $\mathbf{A} - n\mathbf{I}$ vanishes, that is, n is an eigenvalue of $\mathbf{A}$. Now $\mathbf{A}$ has unit rank since every row is a constant multiple of the first row. Thus all its eigenvalues except one are zero. The sum of the eigenvalues of a matrix is equal to its trace, the sum of its diagonal elements, and in this case the trace of $\mathbf{A}$ is equal to n. Thus n is an eigenvalue of A, and one has a nontrivial solution. The solution consists of positive entries and is unique to within a multiplicative constant.

To make $\mathbf{w}$ unique, one can normalize its entries by dividing by their sum. Thus, given the comparison matrix, one can recover the scale.

In this case, the solution is any column of $\mathbf{A}$ normalized. Notice that in $\mathbf{A}$ the reciprocal property $a_{ij} = 1/a_{ji}$ holds; thus, also $a_{ii} = 1$. Another property of $\mathbf{A}$ is that it is *consistent*: its entries satisfy the condition $a_{ik} = a_{ij}a_{jk}$. Thus the entire matrix can be constructed from a set of elements which form a chain across the rows and columns.

In the general case, the precise value of $\frac{w_i}{w_j}$ cannot be given, but instead only an estimate of it as a judgment. For example, consider an estimate of these values by an expert who is assumed to make small perturbations of the coefficients. This implies small perturbations of the eigenvalues. The problem now becomes $\mathbf{A}'\mathbf{w}` = \lambda_{max}\mathbf{w}'$ where λ_{max} is the largest eigenvalue of $\mathbf{A}'$. To simplify the notation, we shall continue to write $\mathbf{Aw} = \lambda_{max}\mathbf{w}$, where $\mathbf{A}$ is the matrix of pairwise comparisons.

The problem now is how good is the estimate of w. Notice that if w is obtained by solving this problem, the matrix whose entries are W_i/W_j is a consistent matrix. It is a consistent estimate of the matrix $\mathbf{A}$. $\mathbf{A}$ itself needs not be consistent. In fact, the entries of $\mathbf{A}$ need not even to be transitive; that is, A_1 may be preferred to A_2 and A_2 to A_3

but A_3 may be preferred to A_1. What we would like is a measure of the error due to inconsistency. It turns out that **A** is consistent if and only if $\lambda_{max} = n$ and that we always have $\lambda_{max} \geq n$

Since small changes in a_{ij} imply a small change in λ_{max}, the deviation of the latter from n is a deviation from consistency and can be represented by $(\lambda_{max} - n)/(n-1)$, which is called the consistency index ($C.I.$). When the consistency has been calculated, the result is compared with those of the same index of a randomly generated reciprocal matrix from the scale 1 to 9, with reciprocals forced. This index is called the random index ($R.I.$). The following Table 5.2 gives the order of the matrix (first row) and the average $R.I.$ (second row):

n	1	2	3	4	5	6	7	8	9	10
$R.I.$	0,00	0,00	0,52	0,89	1,11	1,25	1,35	1,40	1,45	1,49

Table 5.2: Random index estimation according to Saaty, [103].

The ratio of $C.I.$ to the average $R.I.$ for the same order matrix is called the *consistency ratio* ($C.R.$). A consistency ratio of 0,10 or less is positive evidence for informed judgment. We will accept $C.R. \leq 10\%$.

The relations $a_{ij} = 1/a_{ji}$ and $a_{ii} = 1$ are preserved in these matrices to improve consistency. The reason for this is that if stone ♯1 is estimated to be k times heavier than stone ♯2, one should require that stone ♯2 is estimated to be $1/k$ times the weight of the first. If the consistency ratio is significantly small, the estimates are accepted; otherwise, an attempt is made to improve consistency by obtaining additional information. What contributes to the consistency of a judgment are (i) the homogeneity of the elements in a group, not comparing a grain of sand with a mountain; (ii) the sparseness of elements in the group, because an individual cannot hold in mind simultaneously the relations of many more than a few objects; and (iii) the knowledge and care of the decision maker about the problem under study.

5.1.2 Analytical Hierarchy Process structure

The top level of the hierarchy is the focus, it consists of only one element; subsequent levels may each have several elements and because the elements in one level are to be compared with one another against a criterion in the next higher level, the elements in each level must be of the same order of magnitude. According to literature, [102, 32, 74] the proposed hierarchy structure is composed by 5 different levels:

- **Level 1: POLICY** Policy is the target of the procedure, it represent the final aim we want to reach using AHP and it is not involved in the calculation for the lower levels of the structure. In the proposed procedure policy is:
  Fire Risk Assessment for Valuable Contents in Historical Heritage Buildings.

- **Level 2: OBJECTIVES**

Objectives are the top parameters that are involved in the AHP calculation. In the proposed procedure three objectives have been identified:

- *OB1: Evacuation*
- *OB2: Fire Brigade Effectiveness*
- *OB3: Fire and Smoke Spread*

The following Figure 5.1 shows the relationships among Objectives and Policy. The Objectives are the three *control parameters* that have been chosen in this method to assess if risk for Valuable Contents is acceptable with respect to the Policy.

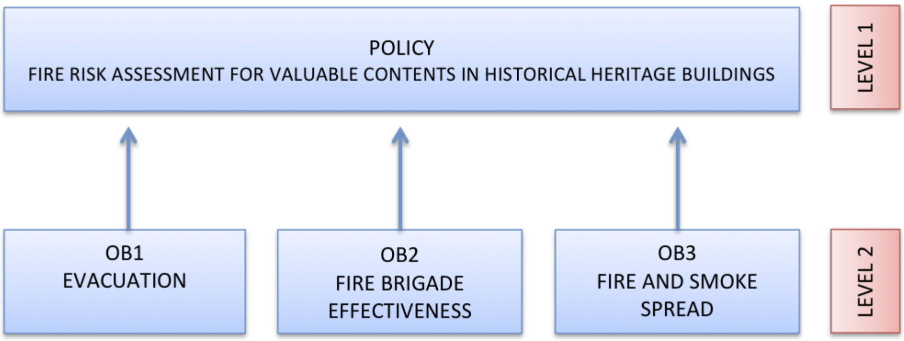


Figure 5.1: Structure of the Analytical Hierarchy: relationships between Objectives (Level 2) and External and Internal Characteristics (Level 3).

Detailed explanations about the three Objectives are reported in paragraph 5.1.4.

Coherently with par. 4.3.1 of chapter 4, from level 3 to level 6, each level is composed by elements belonging to two different sets: the **External Characteristics** and the **Internal Characteristics**.

- **Level 3: CHARACTERISTICS**
  Three External Characteristics and three Internal Characteristics have been chosen . Internal Characteristics are defined for each sector into which the building is divided, External Characteristics are defined once for each building:

  External Characteristics

  - *EC1: Height*
  - *EC2: Vertical Connections*
  - *EC3: Context*

  Internal Characteristics

  - *IC1: Technical Installations*
  - *IC2: Egress Paths*
  - *IC3: Structure*

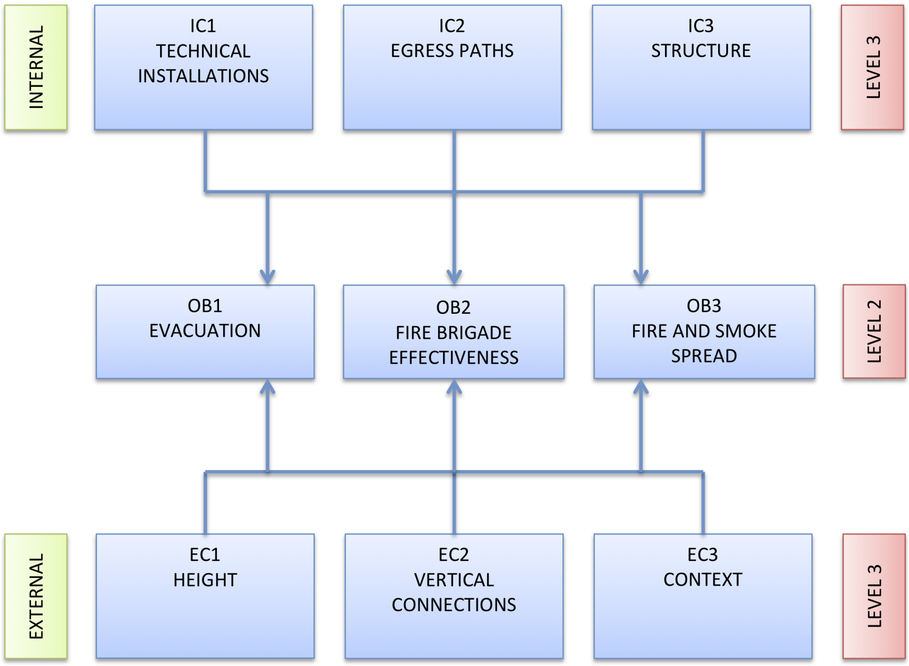


Figure 5.2: Structure of the Analytical Hierarchy: relationships between Objectives (Level 2) and External and Internal Characteristics (Level 3).

The following Figure 5.2 shows the relationships among Objectives and Characteristics; both External and Internal Characteristics are represented.

Detailed explanations about the six Characteristics are reported in paragraph 5.1.5.

- **Level 4: FACTORS**

  Coherently with the paragraph above, each Characteristic is composed by elements belonging to the same set. This way we have the **External Factors**, lower level of the **External Characteristics** and the **Internal Factors**, lower level of the **Internal Characteristics**. External factors are six and they are defined once for the whole building. Internal factors are nine and they are defined for each sector into which the building is divided. We have a total of 15 factors, as reported in the follow:

  External Factors

  - *EF1.1: Number of Levels*
  - *EF1.2: Medium Height*
  - *EF2.1: Stairs*
  - *EF2.2: Double Heights*
  - *EF3.1: Fire Brigade response time*
  - *EF3.2: Surroundings*

  Internal Factors

- *IF1.1: Smoke control system*
- *IF1.2: Detection system*
- *IF1.3: Suppression system*
- *IF1.4: Alarm system*
- *IF2.1: Type of Evacuation Route*
- *IF2.2: Dimension and Layout*
- *IF2.3: Linings and Floorings*
- *IF3.1: Vertical Structure*
- *IF3.2: Horizontal Structure*

The following figures show the relationships among Characteristics and Factors. Figure 5.3 refers to the External Characteristics and Factors while Figure 5.4 refers to the Internal Characteristics and Factors.

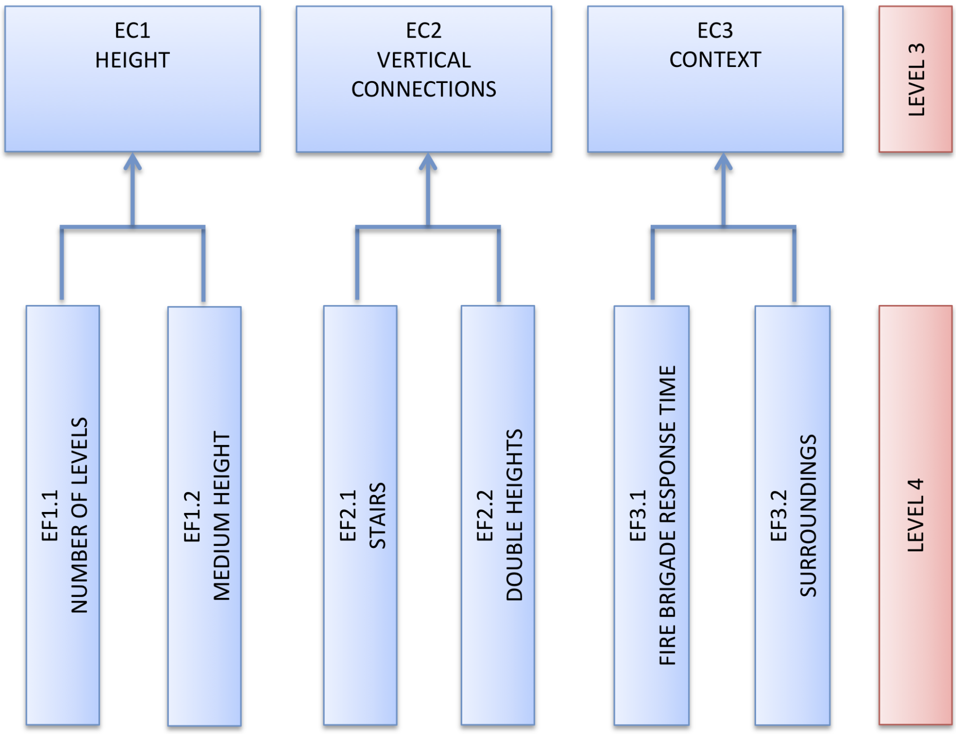


Figure 5.3: Structure of the Analytical Hierarchy: relationships between External Characteristics (Level 3) and External Factors (Level 4).

Detailed explanations about the fifteen Factors are reported in paragraph 5.1.6.

- **Level 5: SUB-FACTORS**
  Sub-Factors are the elementary unit of the Analytical Hierarchy Structure. Sub-Factors are referred to each one of the Factors listed above and they are divided into subsets comprehending a variable number of Sub-Factors. The number of Sub-Factors for each subset depends on the specific Factor to be defined. Total number

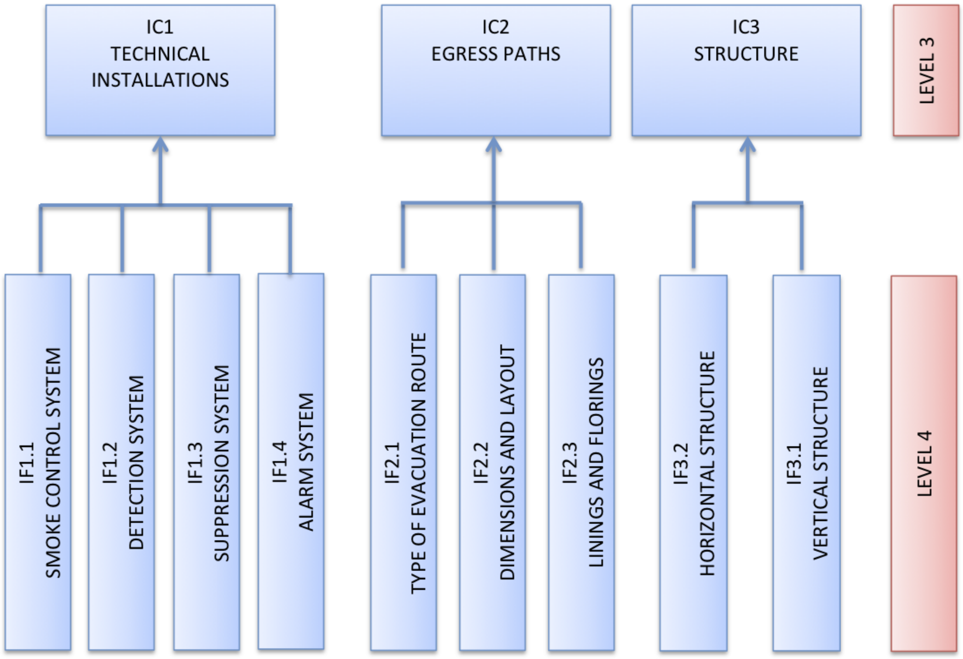


Figure 5.4: Structure of the Analytical Hierarchy: relationships between External Characteristics (Level 2) and External Factors (Level 3).

of Sub-Factors is 37, they are 16 External and 21 Internal. Detailed explanations about the relationships between Sub-Factors and Factors are reported in paragraph 5.1.6.

In the Risk Assessment Method, great attention is given to the level of formation of the Fire Service Team. People in the Fire Service have to be well trained, in a sufficient number respect to the building's dimension and they have to be retrained periodically. To focus on these aspects, an **Extra Factor** (*Fire Service Index - FSI*) has been defined. Such Factor is called "Extra Factor" because it is not a component of the Hierarchic Structure. It is a factor that has an influence on some of the Factors inside the structure but it is out of the hierarchy. Detailed explanations for the *Fire Service Index - FSI* are given in paragraph 5.1.7. In Figure 5.5 the total structure of the Analytical Hierarchy Process is represented.

AHP calculation in Risk Assessment Method

In Risk Assessment Method it is necessary to start giving indexes to the lower level of the structure (Level 5), then a set of matrix calculation gives back as output three risk indexes, one for each Objective. In this paragraph how AHP fits to the proposed Risk Assessment Method is analysed in depth.

As widely explained, we have three Objectives ($OB1, OB2, OB3$) and each one of them is evaluated on the base of 2 sets, each one constituted by three Characteristics ($EC1, EC2, EC3$ and $IC1, IC2, IC3$). We suppose now to have a generic "Cm" Characteristic composed by n Factors and each Factor to be composed by p Sub-Factors. Input data are p risk indexes for each Factor, indexes that have to be assigned following the

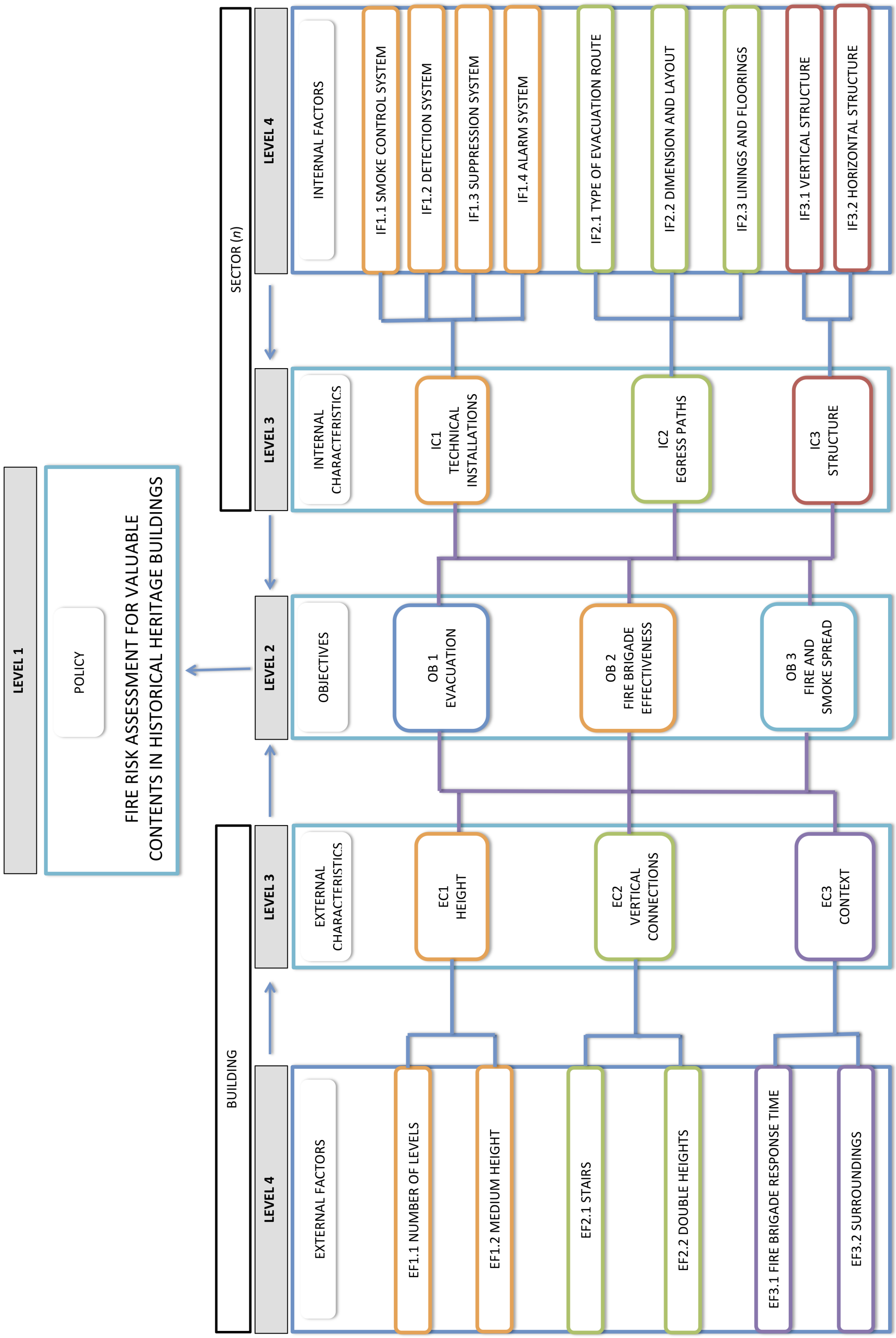


Figure 5.5: Structure of the Analytical Hierarchy for the proposed procedure - Level 5 is not represented.

rules in section 5.1.6. This way it is possible to have a vector $\mathbf{v_{Cm}}$ with "$1 \times n$" dimension containing risk indexes for each n-Factor constituting the "Cm" Characteristic:

$$v_{Cm} = \begin{pmatrix} F1 & \dots & Fn \end{pmatrix} \tag{5.2}$$

In the above notation, vector $\mathbf{v_{Cm}}$ is the vector composed by the risk indexes $(F_1, \dots, F_n)$ of the n Factors constituting the "Cm" Characteristic. This is the only step in which it is necessary to insert data into the method; all the others involved matrixes and vectors have pre-assigned components.

This is the case of weights for Factors composing the "Cm" Characteristic: a closed cluster of technicians, involved in Method's development, assigned the weights performing the first AHP step. For each set of n Factor composing the generic "Cm" Characteristic, an AHP matrix has been built by means of in-pairs comparisons with respect to each one of the three Objectives. AHP gave as output for each Characteristic 3 vectors $\mathbf{w_{Cm}}$ (one for each Objective) having "$n \times 1$" dimension:

$$w_{Cm}^{OB1} = \begin{pmatrix} w_{F1}^{OB1} \\ \vdots \\ w_{Fn}^{OB1} \end{pmatrix} \tag{5.3}$$

$$w_{Cm}^{OB2} = \begin{pmatrix} w_{F1}^{OB2} \\ \vdots \\ w_{Fn}^{OB2} \end{pmatrix} \tag{5.4}$$

$$w_{Cm}^{OB3} = \begin{pmatrix} w_{F1}^{OB3} \\ \vdots \\ w_{Fn}^{OB3} \end{pmatrix} \tag{5.5}$$

In the above notation we indicate as w_{Cm}^{OB1} the vector containing weights of Factors constituting the "Cm" Characteristic with respect to the Objective $OB1$. Each component of the vectors w_{F1}^{OB1} is the weight of the Factor $F1$ with respect to the Objective $OB1$. The vectors can be aggregated into the matrix:

$$W_{Cm} = \begin{array}{c} \begin{matrix} OB1 & OB2 & OB3 \end{matrix} \\ \begin{pmatrix} w_{F1}^{OB1} & w_{F1}^{OB2} & w_{F1}^{OB3} \\ \vdots & \vdots & \vdots \\ w_{Fn}^{OB1} & w_{Fn}^{OB2} & w_{Fn}^{OB3} \end{pmatrix} \end{array} \tag{5.6}$$

Risk indexes for "Cm" Characteristic can then be calculated multiplying vector $\mathbf{v_{Cm}}$ by the matrix $\mathbf{W_{Cm}}$:

$$
\begin{aligned}
v_{Cm} \cdot W_{Cm} = \begin{pmatrix} F1 & \dots & Fn \end{pmatrix} \cdot \begin{pmatrix} w_{F1}^{OB1} & w_{F1}^{OB2} & w_{F1}^{OB3} \\ \vdots & \vdots & \vdots \\ w_{Fn}^{OB1} & w_{Fn}^{OB2} & w_{Fn}^{OB3} \end{pmatrix} = \\
= \begin{pmatrix} \sum_{i=1}^{n} F_i \cdot w_{Fi}^{OB1} & \sum_{i=1}^{n} F_i \cdot w_{Fi}^{OB2} & \sum_{i=1}^{n} F_i \cdot w_{Fi}^{OB3} \end{pmatrix} = \\
= \begin{pmatrix} Cm^{OB1} & Cm^{OB2} & Cm^{OB3} \end{pmatrix} = Cm
\end{aligned} \tag{5.7}
$$

The $\boldsymbol{Cm}$ vector with dimensions "1 × 3" represents the risk indexes of the "Cm" Characteristic with respect to the three Objectives. Once transposed we obtain:

$$
Cm^T = \begin{pmatrix} Cm^{OB1} \\ Cm^{OB2} \\ Cm^{OB3} \end{pmatrix} \tag{5.8}
$$

Since we have 3 Characteristics we calculate the three vectors $C1^T$, $C2^T$ and $C3^T$ that can be aggregated in the matrix:

$$
C_{OB} = \begin{array}{c c} & \begin{array}{ccc} C1 & C2 & C3 \end{array} \\ \begin{array}{c} OB1 \\ OB2 \\ OB3 \end{array} & \begin{pmatrix} C1^{OB1} & C2^{OB1} & C3^{OB1} \\ C1^{OB2} & C2^{OB2} & C3^{OB2} \\ C1^{OB3} & C2^{OB3} & C3^{OB3} \end{pmatrix} \end{array} \tag{5.9}
$$

C_{OB} matrix has in each row the risk indexes of the Characteristics to be combined with the corresponding weights to obtain risk indexes for the Objectives. From C_{OB} matrix it is possible to extract three C^{OB} vectors having "1 × 3" dimensions:

$$
C^{OB1} = \begin{pmatrix} C1^{OB1} & C2^{OB1} & C3^{OB1} \end{pmatrix} \tag{5.10}
$$

$$
C^{OB2} = \begin{pmatrix} C1^{OB2} & C2^{OB2} & C3^{OB2} \end{pmatrix} \tag{5.11}
$$

$$
C^{OB3} = \begin{pmatrix} C1^{OB3} & C2^{OB3} & C3^{OB3} \end{pmatrix}. \tag{5.12}
$$

For the calculation of weights of the Characteristics with respect to the Objectives, a second AHP step has been performed. A Saaty's matrix was built up for each Characteristic putting inside it the expert judgments coming from Delphi Method [refer to section

5.2]. AHP gave as output for each Objective 3 vectors W^{OB} having "3×1" dimension:

$$W^{OB1} = \begin{pmatrix} w_{C1}^{OB1} \\ w_{C2}^{OB1} \\ w_{C3}^{OB1} \end{pmatrix} \tag{5.13}$$

$$W^{OB2} = \begin{pmatrix} w_{C1}^{OB2} \\ w_{C2}^{OB2} \\ w_{C3}^{OB2} \end{pmatrix} \tag{5.14}$$

$$W^{OB3} = \begin{pmatrix} w_{C1}^{OB3} \\ w_{C2}^{OB3} \\ w_{C3}^{OB3} \end{pmatrix}. \tag{5.15}$$

To calculate the risk index for each Objective it is necessary to multiply each C^{OB} vector by the corresponding W^{OB} vector:

$$OB1 = C^{OB1} \cdot W^{OB1} = \begin{pmatrix} C1^{OB1} & C2^{OB1} & C3^{OB1} \end{pmatrix} \cdot \begin{pmatrix} w_{C1}^{OB1} \\ w_{C2}^{OB1} \\ w_{C3}^{OB1} \end{pmatrix} = \sum_{i=1}^{3} Ci^{OB1} \cdot w_{Ci}^{OB1} \tag{5.16}$$

$$OB2 = C^{OB2} \cdot W^{OB2} = \begin{pmatrix} C1^{OB2} & C2^{OB2} & C3^{OB2} \end{pmatrix} \cdot \begin{pmatrix} w_{C1}^{OB2} \\ w_{C2}^{OB2} \\ w_{C3}^{OB2} \end{pmatrix} = \sum_{i=1}^{3} Ci^{OB2} \cdot w_{Ci}^{OB2} \tag{5.17}$$

$$OB3 = C^{OB3} \cdot W^{OB3} = \begin{pmatrix} C1^{OB3} & C2^{OB3} & C3^{OB3} \end{pmatrix} \cdot \begin{pmatrix} w_{C1}^{OB3} \\ w_{C2}^{OB3} \\ w_{C3}^{OB3} \end{pmatrix} = \sum_{i=1}^{3} Ci^{OB3} \cdot w_{Ci}^{OB3} \tag{5.18}$$

The architecture of such calculation is represented in Figure 5.6.

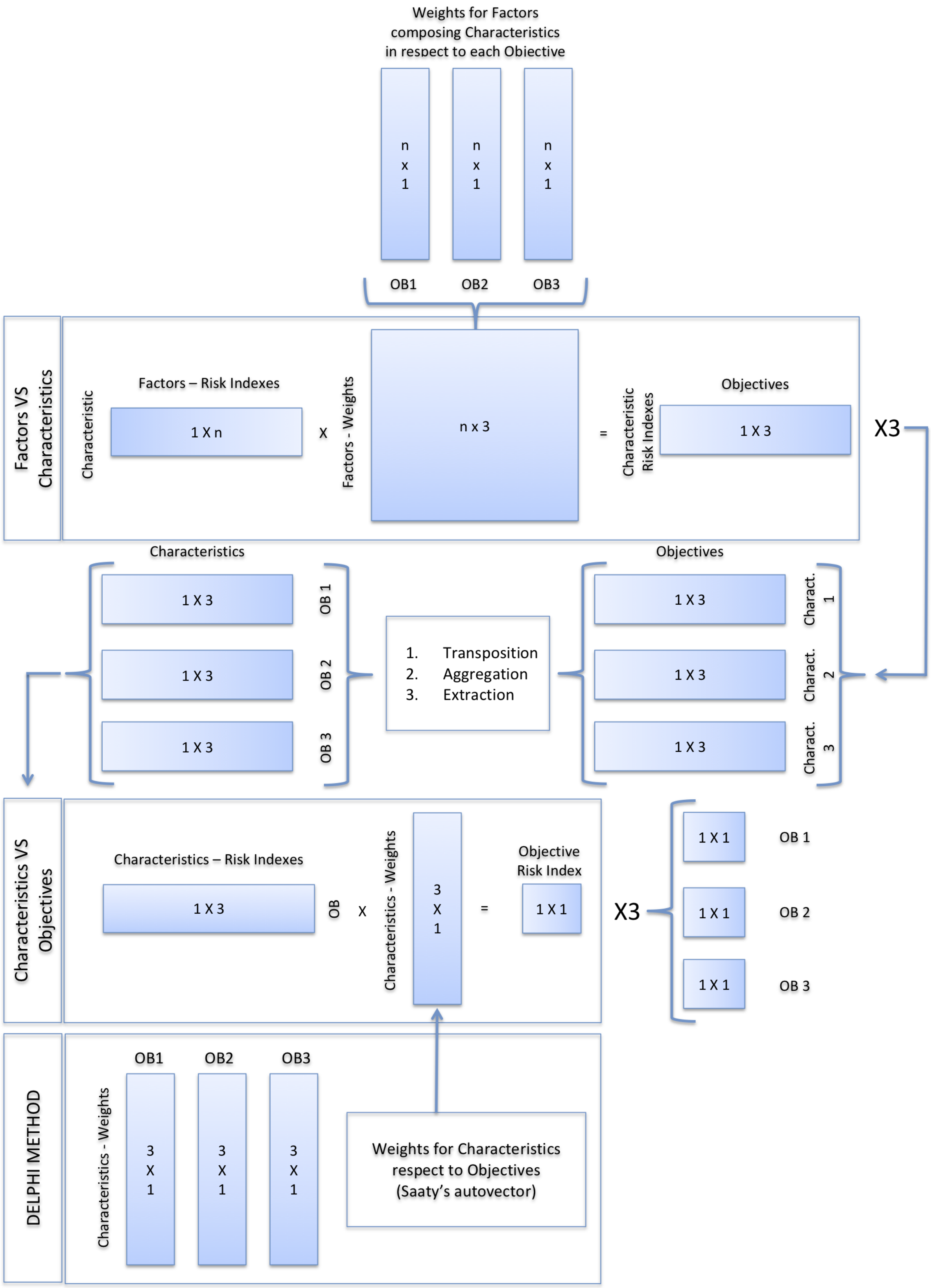


Figure 5.6: Architexture of the AHP calculation in Risk Assessment Method.

5.1.3 Risk scale

To each one of the element of the structure a risk index and a weight are given.

Since we use AHP procedure, for the weights Saaty's scale has been used, as referred in paragraph 5.1.

For risk index we chose a qualitative scale from 0 to 9. Risk indexes are attributed according to the following Table 5.3, that has been developed by the author of the proposed procedure.

Intensity of importance	*Definition*
0	No danger at all
1	Very weak risk
2	Light Risk condition
3	Very moderate risk
4	Moderate risk
5	Risk condition
6	High risk condition
7	Very high risk condition
8	Critical risk condition
9	Absolutely not acceptable risk condition
1.1-1.9	If the elements are very close

Table 5.3: Scale of Risk used in the proposed procedure.

Weights to the elements of the structure have been assigned with two different methods. Weights regarding Level 5 (Sub-Factor) and Level 4 (Factors) were assigned by a close cluster of technicians directly involved in the procedure's development. This because of two main reasons: (*i*) the huge number of parameters that were to be considered and (*ii*) because of the fact that relationships among Factors and Sub-Factors and among Factors and Characteristics, are totally dependent only on technical aspects. On the contrary, weights to the Characteristics (at Level 3) were assigned performing the Delphi method described in paragraph 5.2. This because the relationships among Characteristics and Objectives are in a small number, and on such relationships the reliability of the procedure depends.

5.1.4 Objectives

To reach the Policy at Level 1 of the structure, fire risk for Valuable Contents is evaluated with respect to three control parameter. Such parameters (*Objectives*) occupies Level 2 of the structure and they are defined as in the follow of the paragraph. All the Objectives are evaluated employing both External Characteristics and Internal Characteristics. At the end of the Risk Assessment Method we will have (*i*) 3 risk indexes on the base of the External Characteristics and (*ii*) $3n$ risk indexes on the base of the Internal Characteristics (with n number of *Sectors* into which building is divided).

Each Objective is calculated with the Analytical Hierarchy Process: risk indexes come from the lower level of the structure (Level 2: Characteristics) and weights are assigned with Delphi Method described in section 5.2.

Objective 1: Evacuation - (OB1)
By means of this Objective we want to control how much, in fire event, the building (or sector) is intrinsically dangerous with respect to the Evacuation. As "Evacuation" we mainly consider the evacuation for Valuable Contents due to Damage Limitation Team intervention. Evacuation for occupants, according to the staring hypothesis [refer to section 4.2 in chapter 4], is assured according to fire code's application. An intrinsic link stands between the evacuation of people and of contents since if the first is simple to be executed, also the second takes advantages.

Usually, when the building is open to the public, in case of emergency at first occupants evacuation starts and only at second evacuation for Valuable Contents can start. Evacuation time for people is this way linked to the time in Valuable Contents rescue.

In case of fire occurring when building is not open to the public, a good system of evacuation route for occupants can be used as a good system of paths to get in the building and rescue Valuable Contents.

Objective 1 is defined as follow:

$$OB1 = w_{C1}^{OB1}C1 + w_{C2}^{OB1}C2 + w_{C2}^{OB1}C2 \tag{5.19}$$

where $C1$, $C2$, $C3$ are fore the whole building the External Characteristics ($EC1$, $EC2$, $EC3$) and for each sector the Internal Characteristics ($IC1$, $IC2$, $IC3$).

Objective 2: Fire and smoke develop - (OB2)
By means of this Objective we want to control how much, in fire event, the building (or sector) is intrinsically dangerous with respect to the fire and smokes development. Fire and smoke development is a sensible parameter in order to protect both people and contents. The most you are able not to let fire and smoke spread, the more easy and fast will be the evacuation (both for people and for contents) and lower will be the expected damage.

The most serious damage corresponds with the total loss of the Valuable Contents; it is the limit case we want to avoid. We want also to limit, as far as possible, possible damages to Valuable Contents due to fire. Such damages have been widely studied especially from restorers [87, 88, 33, 34, 52, 56], and from literature it is evident how both high temperature and smoke's sediments are the worst enemies for restorers of all kinds of works of art.

Objective 2 is defined as follow:

$$OB2 = w_{C1}^{OB2}C1 + w_{C2}^{OB2}C2 + w_{C2}^{OB2}C2 \tag{5.20}$$

where $C1$, $C2$, $C3$ are for the whole building the External Characteristics ($EC1$, $EC2$, $EC3$) and for each sector the Internal Characteristics ($IC1$, $IC2$, $IC3$).

Objective 3: Fire brigade effectiveness - (OB3)
By means of this Objective we want to control how much, in fire event, the building (or sector) is intrinsically dangerous with respect to fire brigade effectiveness. The main duty of fire brigades is to intervene saving people and extinguishing fire; in this dissertation

fire brigade effectiveness has to be considered not only with respect to the capability in fire extinguishing, but also with respect to the loss reduction both for building and for Valuable Contents.

Reducing damages means to be effective in extinguishing fire using suitable substances that don't create secondary damages to the Valuable Contents (water is one of the worst extinguisher in relation with the damages that it can create on works of art). Reducing damages means also to be able to limit the fire extension and to be able to intervene with a rescue team for Valuable Contents evacuation.

Objective 3 is defined as follow:

$$OB3 = w_{C1}^{OB3} C1 + w_{C2}^{OB3} C2 + w_{C2}^{OB3} C2 \tag{5.21}$$

where $C1$, $C2$, $C3$ are for the whole building the External Characteristics ($EC1$, $EC2$, $EC3$) and for each sector the Internal Characteristics ($IC1$, $IC2$, $IC3$).

5.1.5 Characteristics

Each group of homogeneous Factors can be aggregated to define the corresponding Characteristic. Indexes for Factors are calculated as shown in Section 5.1.6; weights for each Factor and mathematical relationships in defining the Characteristic are given in the present Section. It is necessary to underline again that weights for Factors with respect to the Characteristics for a certain Objective have been assigned by the developer of the proposed procedure (ref. paragraph 5.1.3). When the Factors are only two, weights have been assigned without the necessity of using the AHP procedure.

5.1.5.1 External Characteristics

EC1 Height

Characteristic $EC1$ is defined basing on the following Factors:

- *EF1.1: Number of Levels*

  [definition on page 71]

- *EF1.2: Medium Height*

  [definition on page 73]

In particular:

$$EC1 = w_{EF1.1} EF1.1 + w_{EF1.2} EF1.2 \tag{5.22}$$

In the previous equation, terms $w_{EF1.1}$ and $w_{EF1.2}$ are established for each one of the Objectives we have in the procedure. In Table 5.4 weights for Factors composing Characteristic $EC1$ are given.

	$OB1$	$OB2$	$OB3$
$w_{EF1.1}$	60%	70%	20%
$w_{EF1.2}$	40%	30%	80%

Table 5.4: Weights for $EF1.1$ and $EF1.2$ respect to the three Objectives (OB).

EC2 Vertical connections

Characteristic $EC2$ is defined basing on the following Factors:

- *EF2.1: Stairs*

  [definition on page 75]

- *EF2.2: Double Heights*

  [definition on page 76]

In particular:

$$EC2 = w_{EF2.1}EF2.1 + w_{EF2.2}EF2.2 \tag{5.23}$$

In the previous equation, the terms $w_{EF2.1}$ and $w_{EF2.2}$ are established for each one of the Objectives we have in the procedure. In Table 5.5 weights for Factors composing Characteristic $EC2$ are given.

	$OB1$	$OB2$	$OB3$
$w_{EF2.1}$	85%	65%	20%
$w_{EF2.2}$	15%	35%	80%

Table 5.5: Weights for $EF2.1$ and $EF2.2$ respect to the three Objectives (OB).

It is important to notice that in the $EC2$ calculation with respect to the *Objective 3: fire and smoke spread*, as explained on pag.77, $EC2$ can be amplified by Sub-Factor $EF2.2.2$ that takes into account the possible presence of spread flues and chimneys. In such a situation, and only for $OB3$ evaluation, $EC2$ becomes :

$$EC_2^{OB3} = IF2.2.2 \times EC2 \tag{5.24}$$

EC3 Context

Characteristic $EC3$ is defined basing on the following Factors:

- *EF3.1: Fire Brigade response time*

  [definition on page 77]

- *EF3.2: Surroundings*

  [definition on page 78]

In particular:

$$EC3 = w_{EF3.1}EF3.1 + w_{EF3.2}EF3.2 \tag{5.25}$$

In the previous equation the terms $w_{EF3.1}$ and $w_{EF3.2}$ are established for each one of the Objectives we have in the procedure. In Table 5.6 weights for Factors composing Characteristic $EC3$ are given.

	$OB1$	$OB2$	$OB3$
$w_{EF3.1}$	65%	65%	60%
$w_{EF3.2}$	35%	35%	40%

Table 5.6: Weights for $EF3.1$ and $EF3.2$ with respect to the three Objectives (OB).

5.1.5.2 Internal Characteristics

IC1 Technical installations

Characteristic $IC1$ is defined basing on the following Factors:

- *IF1.1: Smoke control system*

  [definition on page 80]

- *IF1.2: Detection system*

  [definition on page 82]

- *IF1.3: Suppression system*

  [definition on page 84]

- *IF1.4: Alarm system*

  [definition on page 87]

In particular:

$$IC1 = w_{IF1.1}IF1.1 + w_{IF1.2}IF1.2 + w_{IF1.3}IF1.3 + w_{IF1.4}IF1.4 \tag{5.26}$$

In the previous equation the terms $w_{IF1.1}$, $w_{IF1.2}$, $w_{IF1.3}$ and $w_{IF1.4}$ are established for each one of the Objectives we have in the procedure. The weights are determined by Saaty's matrixes built up making in pairs comparisons among the four Factors with respect to each one of the Objectives. This way we have three matrixes of judgments from which, with AHP, the weights are calculated. For each one of the matrix, $C.R.$ is checked. Output of the method for each one of the matrix is a 4×1 autovector containing weights for each Factor with respect to the considered Objective. Since we have 3 Objectives, we are able to aggregate such vectors as quoted in Table 5.7.

Matrix 5.27 has been built with respect to *Objective 1: Evacuation*; $C.R. = 7,2\%$.

$$\begin{array}{c} \\ IF1.1 \\ IF1.2 \\ IF1.3 \\ IF1.4 \end{array} \begin{array}{c} \begin{array}{cccc} IF1.1 & IF1.2 & IF1.3 & IF1.4 \end{array} \\ \begin{pmatrix} 1 & 1 & 2 & 1/2 \\ 1 & 1 & 2 & 1 \\ 1/2 & 1/2 & 1 & 1 \\ 2 & 1 & 1 & 1 \end{pmatrix} \end{array} \tag{5.27}$$

Matrix 5.28 has been built with respect to *Objective 2: Fire brigade effectiveness*; $C.R. = 0,0\%$.

$$\begin{array}{c} \\ IF1.1 \\ IF1.2 \\ IF1.3 \\ IF1.4 \end{array} \begin{array}{c} \begin{array}{cccc} IF1.1 & IF1.2 & IF1.3 & IF1.4 \end{array} \\ \begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{pmatrix} \end{array} \tag{5.28}$$

Matrix 5.29 has been built with respect to *Objective 3: Fire and smoke spread*; $C.R. = 0,4\%$.

$$\begin{array}{c} \\ IF1.1 \\ IF1.2 \\ IF1.3 \\ IF1.4 \end{array} \begin{array}{c} \begin{array}{cccc} IF1.1 & IF1.2 & IF1.3 & IF1.4 \end{array} \\ \begin{pmatrix} 1 & 2 & 1 & 3 \\ 1/2 & 1 & 1/2 & 2 \\ 1 & 2 & 1 & 3 \\ 1/3 & 1/2 & 1/3 & 1 \end{pmatrix} \end{array} \tag{5.29}$$

In Table 5.7 the weights calculated for Factors composing Characteristic $IC1$ are resumed.

	$OB1$	$OB2$	$OB3$
$w_{IF1.1}$	24%	25%	35%
$w_{IF1.2}$	28%	25%	18%
$w_{IF1.3}$	18%	25%	35%
$w_{IF1.4}$	30%	25%	12%

Table 5.7: Weights for $IF1.1$, $IF1.2$, $IF1.3$ and $IF1.4$ with respect to the three Objectives (OB).

IC2 Egress paths

Simple evaluation methods for the quality of egress paths are described in literature [117, 77]. They take into account the type of escape routes, the distance from the nearest exit, the number of floors, the egress paths width against the number of occupants etc. Here are only considered: Type, Dimensions and Layout, Linings and Floorings. Characteristic $IC2$ is defined basing on the following Factors:

- *IF2.1: Type of Evacuation Route*

  [definition on page 89]

- *IF2.2: Dimension and Layout*

[definition on page 92]

- *IF2.3: Linings and Floorings*

  [definition on page 93]

In particular:

$$IC2 = w_{IF2.1}IF2.1 + w_{IF2.2}IF2.2 + w_{IF2.3}IF2.3 \tag{5.30}$$

In the previous equation the terms $w_{IF2.1}$, $w_{IF2.2}$ and $w_{IF2.3}$ are established for each one of the Objectives we have in the procedure. The weights are, like for $IC1$, determined by Saaty's matrixes of judgments using AHP. For each one of the matrix, $C.R.$ is checked.

Matrix 5.31 has been built with respect to *Objective 1: Evacuation*; $C.R. = 6,1\%$.

$$\begin{array}{c} \\ IF2.1 \\ IF2.2 \\ IF2.3 \end{array} \begin{array}{c} \begin{array}{ccc} IF2.1 & IF2.2 & IF2.3 \end{array} \\ \begin{pmatrix} 1 & 2 & 3 \\ 1/2 & 1 & 3 \\ 1/3 & 1/3 & 1 \end{pmatrix} \end{array} \tag{5.31}$$

Matrix 5.32 has been built with respect to *Objective 2: Fire brigade effectiveness*; $C.R. = 5,4\%$.

$$\begin{array}{c} \\ IF2.1 \\ IF2.2 \\ IF2.3 \end{array} \begin{array}{c} \begin{array}{ccc} IF2.1 & IF2.2 & IF2.3 \end{array} \\ \begin{pmatrix} 1 & 2 & 2 \\ 1/2 & 1 & 2 \\ 1/2 & 1/2 & 1 \end{pmatrix} \end{array} \tag{5.32}$$

Matrix 5.33 has been built with respect to *Objective 3: Fire and smoke spread*; $C.R. = 0,0\%$.

$$\begin{array}{c} \\ IF2.1 \\ IF2.2 \\ IF2.3 \end{array} \begin{array}{c} \begin{array}{ccc} IF2.1 & IF2.2 & IF2.3 \end{array} \\ \begin{pmatrix} 1 & 1/2 & 1/2 \\ 2 & 1 & 2 \\ 2 & 1 & 1 \end{pmatrix} \end{array} \tag{5.33}$$

In Table 5.8 the weights calculated for Characteristic $IC2$ are resumed.

	$OB1$	$OB2$	$OB3$
$w_{IF2.1}$	54%	50%	20%
$w_{IF2.2}$	30%	29%	40%
$w_{IF2.3}$	16%	21%	40%

Table 5.8: Weights for $IF2.1$, $IF2.2$ and $IF2.3$ respect to the three Objectives (OB).

IC3 Structure
With this Characteristic the type of structure present in the sector is considered. Characteristic $EC3$ is defined basing on the following Factors:

- *IF3.1: Vertical Structure*

  [definition on page 94]

- *IF3.2: Horizontal Structure*

  [definition on page 94]

In particular:

$$IC3 = w_{IF3.1} IF3.1 + w_{IF3.2} IF3.2 \tag{5.34}$$

In the previous equation the terms $w_{IF3.1}$ and $w_{IF3.2}$ are established for each one of the Objectives we have in the procedure. In Table 5.9 weights for Characteristic $IC3$ are given.

	$OB1$	$OB2$	$OB3$
$w_{IF3.1}$	40%	30%	20%
$w_{IF3.2}$	60%	70%	80%

Table 5.9: Weights for $IF3.1$ and $IF3.2$ respect to the three Objectives (OB).

5.1.6 Factors and Sub-Factors

In this paragraph all the logic and mathematical relationships among Factors and Sub-Factors are described in details. All the elements are catalogued, as explained in the previous section, in two sets: External and Internal. For each Sub-Factor its potential dependance on management strategies, directly related to the manager's decisions, is highlighted.

In our intentions, each one of the Sub-Factors has to resume in itself all the significant configurations that the specific element can assume in reality. For every listed configuration, a corresponding risk index is attributed to the Sub-Factor. Each one of the Factors and Sub-Factors is marked with a code composed by two letters and two or three numbers.

Generic code for Factor $XY\gamma.\sigma$:

- XY can assume letters "EF'' for *External Factors* and "IF'' for *Internal Factors*;
- γ assumes a number referred to the Characteristic that is composed by that Factor;
- σ is the progressive number of the Factor.

Generic code for Sub-Factors $XY\gamma.\sigma.\delta$:

- XY can assume letters "EF'' for *External Sub-Factors* and "IF'' for *Internal Sub-Factors*;

- γ assumes a number referred to the Characteristic that is composed by that Factor and Sub-Factor;
- σ assumes a number referred to the Factor that is composed by that Sub-Factor;
- δ is the progressive number of the Sub-Factor.

5.1.6.1 External Factors and Sub-Factors

The Factors here described are related to the features of the building that can be detected with a macro-scale analysis.

EF1.1 Number of levels

The Factor that considers the number of building's levels is defined as follow:

$$EF1.1 = EF1.1.1 \times EF1.1.2 \times EF1.1.3 \tag{5.35}$$

where:

- *EF1.1.1* is the Sub-Factor dealing with the number of levels out of ground;
- *EF1.1.2* is the Sub-Factor considering the number of underground levels;
- *EF1.1.3* is the Sub-Factor considering the presence of an attic and its destination of use.

In Figure 5.7 the relationships between Factor $EF1.1$ and Sub- Factors $EF1.1.1$, $EF1.1.2$, $EF1.1.3$ are shown.

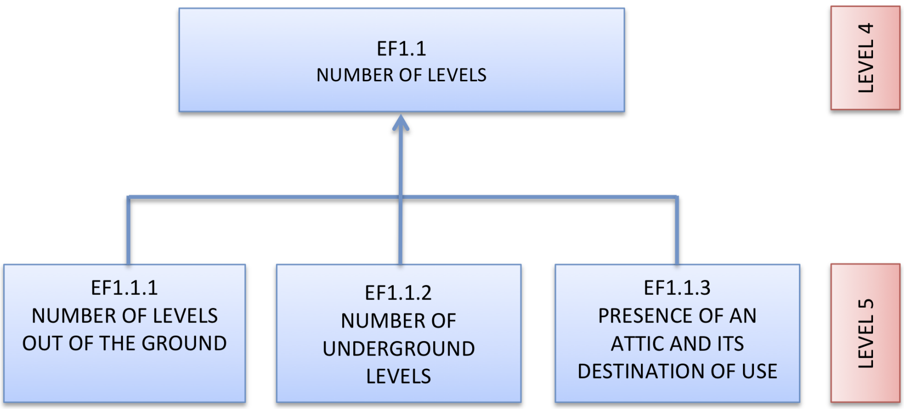


Figure 5.7: Relationships between Factor $EF1.1$ and Sub- Factors $EF1.1.1$, $EF1.1.2$, $EF1.1.3$.

<u>*EF1.1.1*</u>

Three levels historical buildings are the most common in Europe. If the building has staggered floors, the number of levels is calculated looking at the facade with the higher number of levels. High-rise buildings (height$\geq$ 22m) are not relevant for Italian historical buildings. Table 5.10 shows the different building configurations (in the first column) and the corresponding risk indexes attributed to $EF1.1.1$.

Number of levels	$EF1.1.1$
1	1
2	3
3	6
≥ 3	8

Table 5.10: Risk indexes for $EF1.1.1$.

Usually in Italy historical buildings can be composed by:

- first "service" level with low height (this level can be partially underground):
- second level that is *"piano nobile"*; the most important level that can have an higher height than other levels (6-8 meters);
- third and fourth levels with a lower height than second floor.

In terms of fire brigade intervention, accessing from the extern to a 3 levels building is quite common with the use of 10m height ladders. Accessing to an higher building can create some problems: trucks equipped with a ladder of 30m maximum height need huge spaces in front of the building to be used (refer to pag. 79). This is the reason why in the previous Table 5.10, passing from first to second floor is less dangerous than passing from second to third.

EF1.1.2
It is here checked the presence of underground levels. Underground levels are often critical because of the fact that such spaces are used as storage rooms or deposits (often deposits of Valuable Contents). Table 5.11 shows the different building configurations (in the first column) and the corresponding risk indexes attributed to $EF1.1.2$.

Number of underground levels	$EF1.1.2$
0	1,0
1	1,1
2	1,2

Table 5.11: Risk indexes for $EF1.1.2$.

EF1.1.3
It is here checked the presence of attics. Attics are often critical for two reasons: (i) such spaces are used as storage rooms or deposits (often deposits of Valuable Contents) and (ii) attics are the weakest point for fire protection. Usually, roofs of historical buildings

are made of wood and in fire event, in an attic, fire is often able to spread all over the building. Choosing the destination of use of the attic is a proper management strategy.

If there is an attic, a *"Sector"* has to be identified with the attic itself (refer to the *"Sector"* definition in paragraph 4.3.1, chapter 4).

Table 5.12 shows the different building configurations (in the first column) and the corresponding risk indexes attributed to $EF1.1.3$.

Presence of the attic	*Destination of use*	$EF1.1.3$
no		1
yes	empty	1,1
yes	with technical installation inside	1,2
yes	used as storage area	1,3

Table 5.12: Risk indexes for $EF1.1.3$.

EF1.2 Medium Height

The Factor that considers the building's height is defined on the basis of the following parameter:

$$H_M = \frac{\sum_{i=1}^{n} \alpha_{pi} A_i H_i}{\sum_{i=1}^{n} A_i} \tag{5.36}$$

where:

- $A_i = EF1.2.1$ is the Sub-Factor dealing with the partial surface of the building's area with H_i height;
- $H_i = EF1.2.2$ is the Sub-Factor considering the partial height of the building's area with A_i surface;
- $\alpha_{pi} = EF1.2.3$ is the Sub-Factor considering if the i area with H_i height and A_i surface is opened to the public;
- n is the number of areas with H_i height and A_i surface individuated in the building.

Height H_i is always calculated under the eaves. By means of the intermediate parameter H_M, height of the different parts of the building is weighted with the surface of that area.

Figure 5.8 shows the relationships between Factor $EF1.2$, parameter H_M and Sub-Factors $EF1.2.1$, $EF1.2.2$, $EF1.2.3$.

EF1.2.3

The Sub-Factor $EF1.2.3$ can assume values in Table 5.13 for each i area into which building is divided.

Choosing to let some sensible parts of the building open to the public or not, is a proper management strategy.

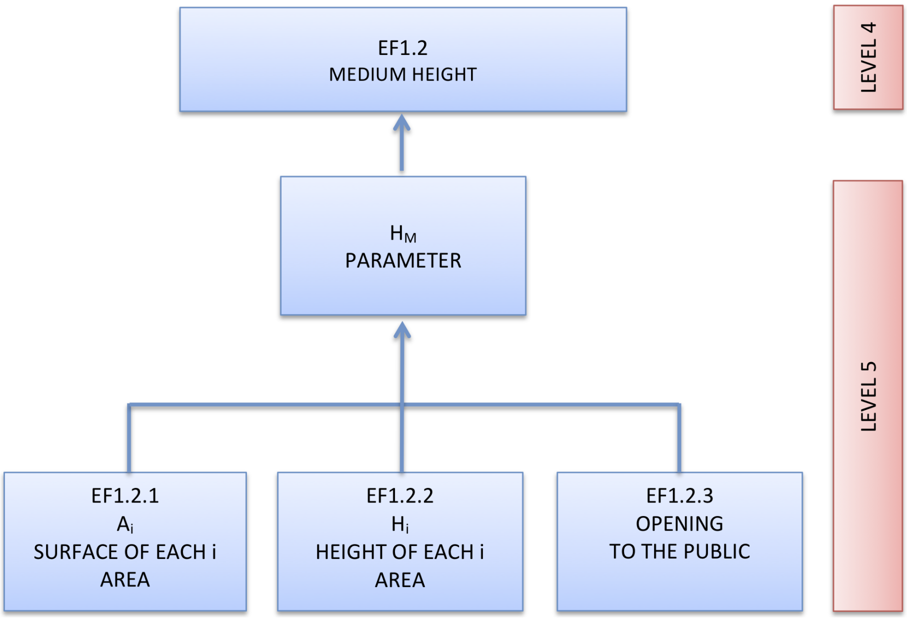


Figure 5.8: Relationships between Factor $EF1.2$, parameter H_M and Sub- Factors $EF1.2.1$, $EF1.2.2$, $EF1.2.3$.

Opening to the public	$EF1.2.3$
not open to the public	1
partially open to the public	1,1
open to the public	1,3

Table 5.13: Values for $EF1.2.3$

Once calculated the H_M parameter, $EF1.2$ index is attributed on the base of the following Table 5.14. Height of 22 m is the upper limit because, over that height, we have to consider the buildings as high rise buildings.

H_M	$EF1.2$
$H_M \leq 3$	0
$3 < H_M \leq 5$	3
$5 < H_M \leq 10$	4
$10 < H_M \leq 15$	6
$15 < H_M \leq 22$	7
$22 \leq H_M$	9

Table 5.14: Risk indexes for $EF1.2$.

EF2.1 Stairs

Stairs have to be considered as important escape routes not only for people but also for Valuable Contents evacuation and it is necessary to take into account the definition of "safe stair" given by the fire-code. Stairs that can be technically defined as "safe" egress stairs (E_{ss} according to the following definitions), are automatically considered as stairs able to be used to evacuate Valuable Contents. It is then necessary to count also other stairs present in the building because in Historical Heritage Buildings it is possible to have some stairs that can be considered equivalent to the "safe" ones in terms of occupants exodus and Valuable Contents evacuation (such stairs are here defined E_{es}).

The Factor that consider the presence and the number of stairs in the building is defined as follow:

$$EF2.1 = 3 + \lambda\Delta S + (1 - \lambda)S_R \tag{5.37}$$

where:

$$S_R = \frac{D_s}{E_{ts}} \tag{5.38}$$

$$\Delta S = D_s - E_{ts} \tag{5.39}$$

and

$\lambda = 0,6$ is the importance of the parameter ΔS with respect to the parameter S_R.

We further define:

- $D_s = EF2.1.1$ is the Sub-Factor dealing with the desired number of stairs according to the codes. It represents the code's prescription, it is the number of stairs that the building needs if the fire code is applied with no law dispensation.;
- $E_{ts} = E_{ss} + E_{es}$ is the Sub-Factor considering the total number of egress stairs present in the building;
- $E_{ss} = EF2.1.2$ is the parameter considering the total number of "safe" egress stairs present in the building. A stair is considered "safe" when has the characteristics that the fire code requests;
- $E_{es} = EF2.1.3$ is the Sub-Factor considering the total number of "equivalent safe" egress stairs present in the building. A stair is considered "equivalent safe" when it

has not the characteristics that the fire code requests but it can be used as egress stairs because of the special situation in the historical building;

- $E_{tot} = E_{ts} + E_{us}$ is the parameter considering the total number of stairs present in the building, both unsafe, safe and used as egress stairs;

- E_{us} is the number of unsafe stairs present in the building. A stair is considered "unsafe" when it is not possible at all to use it as an egress stair.

Building's manager, deciding the tour path, can establish which ones the safe egress stairs (determining the E_{ss} number) are. Building's manager has the duty of establishing, with technicians, which the stairs to be used to evacuate Valuable Contents are.

Figure 5.9 shows the relationships between Factor $EF2.1$ and Sub-Factors $EF2.1.1$, $EF2.1.2$, $EF2.1.3$.

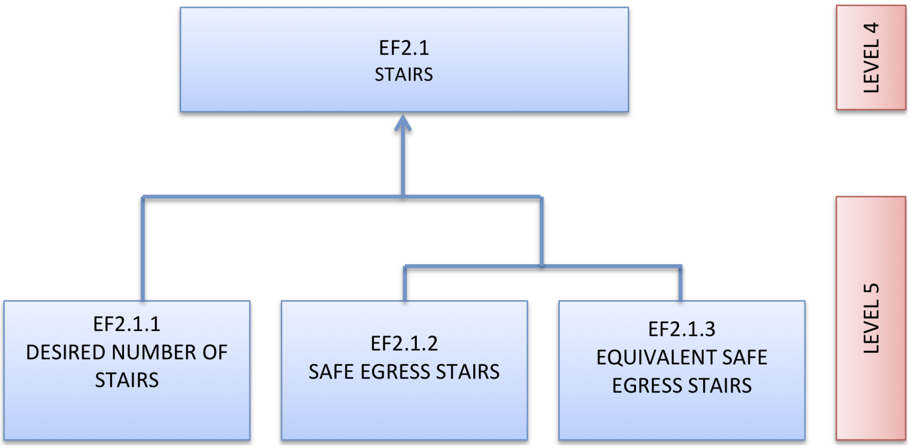


Figure 5.9: Relationships between Factor $EF2.1$ and Sub-Factors $EF2.1.1$, $EF2.1.2$, $EF2.1.3$.

EF2.2 Vertical Connections

This Factor considers the presence of vertical connections among the floors, due to architectonical features. The presence of salons, theatres, halls can create obstacles in evacuation both of people and Valuable Contents and it is a critical point in fire spread. This Factor is composed by two Sub-Factors:

- $EF2.2.1$ is a Sub-Factor that considers the possible presence of double heights in the building;

- $EF2.2.2$ is a Sub-Factor that considers the possible presence of spread flues and chimneys in the building.

$EF2.2.1$ acts in all the Objectives (ref. paragraph 5.1.4) while $EF2.2.2$ has to be considered only with respect to the *Objective 3: Fire and smoke spread*.

Presence of double heights	$EF2.2.1$
no	0
1 double height: 2 levels height	5
1 double height: 3 levels height	7
more than one double height	9

Table 5.15: Risk indexes for $EF2.2.1$

EF2.2.1
Sub-Factor $EF2.2.1$ can assume the values in Table 5.15:

In Table 5.15, in the second row, it is considered that in the building there is just one double height that has the height of two floors. In the third row it is considered that in the building there is one double height that has the height of three floors. The fourth row means that in the building there is more than one double height with the above characteristics.

EF2.2.2
Sub-Factor $EF2.2.2$ can assume the values in Table 5.16. This Sub-Factor acts only as

Presence of flues and chimneys	$EF2.2.2$
no	1,0
spread flues and chimneys directly detected	1,2
possible presence of ancient flues and chimneys	1,3

Table 5.16: Values for $EF2.2.2$

an amplification parameter with respect to the evaluation of $EC2$ respect to *Objective 3: Fire and smoke spread*, ref. to pag 66.

EF3.1 Fire brigade response time
In this Factor the fire brigade response time is considered. In some special case, we have on site firemen inside Historical Heritage Buildings (these cases have to be discussed on the base of the regulations; i.e. public shows inside historical building). The time required for a suitably equipped fire brigade team to reach the site of the fire is essential in terms of limiting the extent of fire and the damage. Response time is strictly linked to the distance between fire station and building and the probability of traffic jam has to be included in the evaluation. It is assumed that fire brigade equipment is adapted to the task they may have to fulfill. The Sub-Factor $EF3.1.1$ is totally coincident with the Factor $EF3.1$.
Factor $EF3.1$ can assume the values in Table 5.17:

The permanent presence of trained staff facilitates and accelerates the first intervention on a starting fire and this way can limit the extent of damage. If a $FireServiceIndex \leq 2$ [refer to paragraph 5.1.7] comes from the calculation, it is possible to take a step up with

Fire brigade response time	$EF3.1$
0-5 min (on site fireman)	2
5-10 min	4
10-15 min	6
>15 min	8

Table 5.17: Risk indexes for $EF3.1$

respect to the real situation in the upper table. Building's manager can take special agreements with the fire brigades to reduce their intervention time.

EF3.2 Surroundings

Surroundings of the analysed building are here checked. $EF3.2$ factor is defined as follow:

$$EF3.2 = EF3.2.3 \times I_D \tag{5.40}$$

where:

- $EF3.2.3$ is a Sub-Factor considering the position of the building with respect to the urban configuration of the city;
- I_D is a parameter composed by Sub-Factor $EF3.2.1$ and $EF3.2.2$.

I_D is defined as follow:

$$I_D = \frac{\sum_{i=1}^{n}(\lambda G_i + (1-\lambda)A_i)}{n} \tag{5.41}$$

where:

- n is the number of building's sides;
- λ=0,5 is the importance of the parameter G_i with respect to the parameter A_i;
- $G_i = EF3.2.1$ is the Sub-Factor that takes into account the distance between the analysed side and opposite buildings;
- $A_i = EF3.2.2$ is the Sub-Factor that takes into account the accessibility of the analysed side.

$EF3.2.1$ and $EF3.2.2$ are attributed for each side of the building.

Figure 5.10 shows the relationships between Factor $EF3.2$ and Sub-Factors $EF3.2.1$, $EF3.2.2$, $EF3.2.3$.

EF3.2.1

Distance between buildings is an indication for risk: (*i*) of fire propagation between facing building and (*ii*) accessibility by fire brigade and consequent evacuation both for occupants

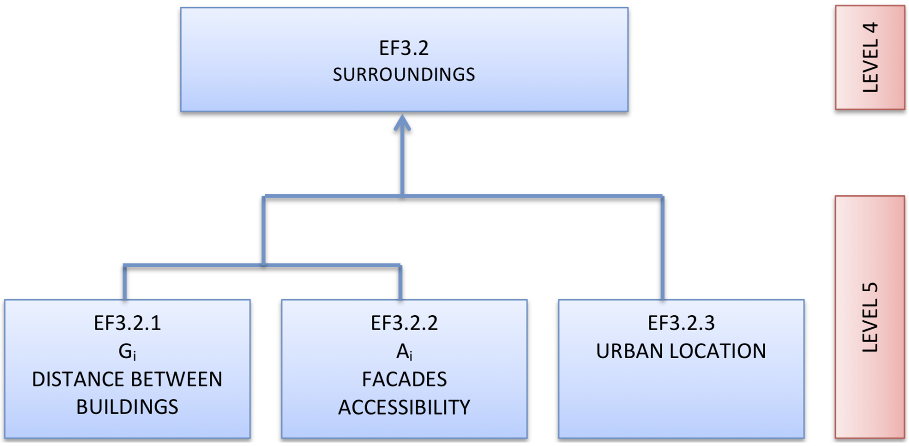


Figure 5.10: Relationships between Factor $EF3.2$ and Sub-Factors $EF3.2.1$, $EF3.2.2$, $EF3.2.3$.

and Valuable Contents. The degree of implementation is proportional to the number of sides and takes into account the risk of fire propagation for every facade (side) of the building. The opposite building can sometimes be another part of the same building we are analysing.

$EF3.2.1$ can represent the width of the streets around the building. If the street is narrower than 3,5 m, fire brigades can use only ladders able to reach 10 m of height. If streets are wider than 3,5 m fire brigades can use ladders able to reach 30 m of height.

Sub-Factor $EF3.2.1$ can assume the values in Table 5.18.

D=Distance between facade and opposite buildings	$EF3.2.1$
3,5 m$>D$ (not accessible for the fire brigades' truck)	9
3,5 m$\leq D \leq$6 m	7
6 m$< D \leq$9 m	5
9 m$< D \leq$20 m	3
$D >$20 m	1

Table 5.18: Risk indexes for $EF3.2.1$

EF3.2.2

The accessibility of the cultural heritage for the fire brigade and their fire fighting equipment is important for a fast and efficient fire fighting intervention, limitation of the fire losses and salvation of contents. The accessibility has to be evaluated in function of the longest time firemen have to overcome to reach the least accessible potential fire location with suitable fire fighting means. Access time is part of the total time, including arrival time for the fire brigade to start fire fighting. Parameters influencing these times are:

- the number of facades accessible for fire engines (it is here considered accessible a facade facing a street);
- the geometry i.e. depth, width, number of floors of a building;

Sub-Factor $EF3.2.2$ can assume the values in Table 5.19.

Accessibility of each side	$EF3.2.2$
not accessible	9
less than 1 window accessible for each level	7
1 window accessible for each level	6
more than 1 window accessible for each level	5
all windows for each level accessible	4

Table 5.19: Risk indexes for $EF3.2.2$

In Table 5.19 we take into account the number of windows accessible from the outside for each level of the building. In the second row we consider the fact that is possible to have at least 1 window accessible but not for each level of the building. In the second row we consider to have at least 1 window accessible for each level of the building.

EF3.2.3
This Sub-Factor is dependent on the urban location of the analysed building. Sub-Factor $EF3.2.3$ can assume the values in Table 5.20.

Urban location	$EF3.2.3$
inside historical center and traffic restricted area	1,4
inside historical center	1,2
outside historical center	1,0

Table 5.20: Values for $EF3.2.3$

5.1.6.2 Internal Factors and Sub-Factors

The Factors here described are related to the features of each one of the *"Sectors"* into which the building is divided.

IF1.1 Smoke control system
In cultural heritage buildings, smoke control:

- contributes to the safe evacuation of people between substantial times;
- limits the smoke damage to cultural heritage content.

The grade of implementation has to be evaluated regarding the efficiency of prohibiting smoke to spread beyond the room of origin of the fire during its expected duration. The efficiency of smoke control systems depends upon the activation of the smoke control system (manual versus automatic) and the type of system:

- natural ventilation through openings;

- mechanical ventilation;
- pressurisation and ventilation (natural, mechanical or mixed) for smoke.

$IF1.1$ factor is defined as follow:

$$IF1.1 = IF1.1.1 \times IF1.1.2 \tag{5.42}$$

where:

- $IF1.1.1$ is a Sub-Factor considering the characteristics of the smoke control system;
- $IF1.1.2$ is a Sub-Factor considering the maintenance of the smoke control system.

Figure 5.11 shows the relationships between Factor $IF1.1$ and Sub-Factors $IF1.1.1$ and $IF1.1.2$.

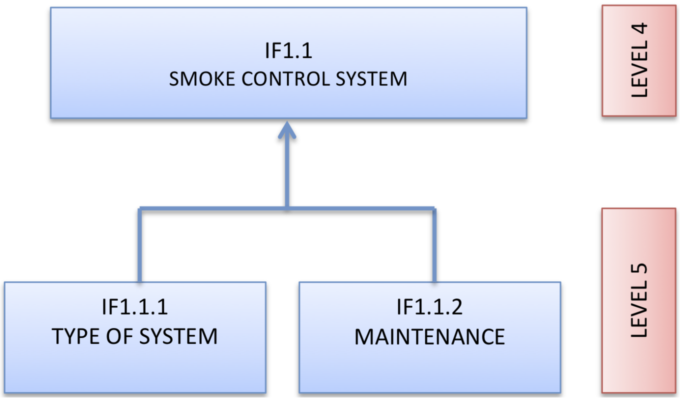


Figure 5.11: Relationships between Factor $IF1.1$ and Sub-Factors $IF1.1.1$ and $IF1.1.2$.

<u>*IF1.1.1*</u>

Sub-Factor $IF1.1.1$ can assume values in Table 5.21.

	Activation of smoke control system		
Type of smoke control system	automatic	manual	no smoke control system
natural ventilation through openings near ceiling	2	6	7
mechanical ventilation	2	6	7
pressurization and natural or mechanical or mixed ventilation for exiting smoke	1	4	7

Table 5.21: Risk indexes for $IF1.1.1$

<u>*IF1.1.2*</u>

Maintenance of fire safety systems is essential for their reliability/efficiency. Building's manager has the duty to organize the periodical maintenance of the systems. Also periodic testing of the fire safety systems is necessary to keep their reliability and efficiency. According to Italian law DM 10/03/98 [9], periodical maintenance to fire systems has semestral periodicity. Sub-Factor $IF1.1.2$ can assume the values in Table 5.22.

Periodicity of maintenance	$IF1.1.2$
once a year	1,5
twice a year	1,0

Table 5.22: Values for $IF1.1.2$

IF1.2 Detection system

This Factor is evaluated on the basis of the distribution and the type of detectors. $IF1.2$ factor is defined as follow:

$$IF1.2 = IF1.2.3 \times I_{DET} \tag{5.43}$$

where:

- $IF1.2.3$ is a Sub-Factor considering the maintenance of the detection system;
- I_{DET} is a parameter composed by Sub-Factor $IF1.2.1$ and $IF1.2.2$.

I_{DET} is defined as follow:

$$I_{DET} = \lambda D_{Ds} + (1 - \lambda) T_{Ds} \tag{5.44}$$

where:

- λ=0,5 is the importance of the parameter D_{Ds} with respect to the parameter T_{Ds};
- $D_{Ds} = IF1.2.1$ is the Sub-Factor that takes into account the distribution of the system in the sector;
- $T_{Ds} = IF1.2.2$ is the Sub-Factor that takes into account the type of system.

If in the sector there are Laser Detection System or Air Sampling Detection System, risk index for $IF1.2$ is **1**.
If there is no detection system nor in the rooms or in the escape routes, risk index for $IF1.2$ is **9**.

Figure 5.12 shows the relationships between Factor $IF1.2$ and Sub-Factors $IF1.2.1$, $IF1.2.2$ and $IF1.2.3$.

IF1.2.1

Sub-Factor $IF1.2.1$ measures the quantity of detectors in the sector and comprehends if there are detectors in escape routes. It is to underline that some detection systems are

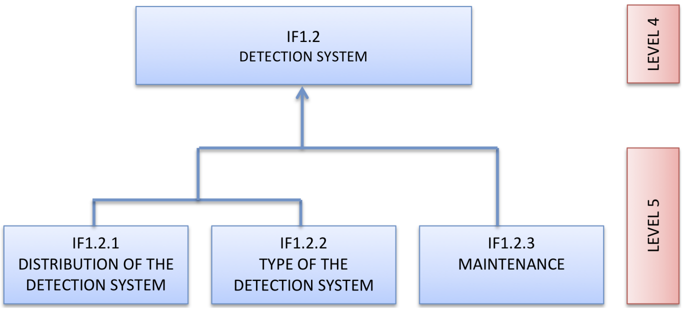


Figure 5.12: Relationships between Factor $IF1.2$ and Sub-Factors $IF1.2.1$, $IF1.2.2$ and $IF1.2.3$.

not bonded to the number of detectors (i.e. Laser Detection System and Air Sampling Detection System). Sub-Factor $IF1.2.1$ can assume the values in Table 5.23.

Distribution of detectors		$IF1.2.1$
Detectors in rooms	Detectors in escape route	
none in the rooms	no	9
	yes	6
at least one in every room	no	6
	yes	4
more than one in every room	no	2
	yes	1

Table 5.23: Risk indexes for $IF1.2.1$

IF1.2.2

Sub-Factor $IF1.2.2$ checks the type of system and depends also on the detector's power supply and data transmission system (WI-FI or wired). Sub-Factor $IF1.2.2$ can assume the values in Table 5.24.

Type of detection system						
Heat detectors		Smoke detectors		Heat and smoke det. with CPU		Laser det. or Air Sampling det. system
Wireless	Wired	Wireless	Wired	Wireless	Wired	
6	5	5	4	3	2	1

Table 5.24: Risk indexes for $IF1.2.2$

IF1.2.3

Sub-Factor $IF1.2.3$ can assume values in Table 5.25.

Periodicity of maintenance	$IF1.2.3$
once a year	1,5
twice a year	1,0

Table 5.25: Values for $IF1.2.3$

IF1.3 Suppression system

Both automatic and portable fire suppression means are covered by this Factor. Ultimately the efficiency of both aspects has to be evaluated on the basis of their capacity to extinguish a starting fire. For automatic fire suppression systems the type and the location of heads are important.

The efficiency of portable extinguishers depends entirely on the presence of trained people; one of the duties of the building's manager is to make the staff trained. Refer to paragraph 5.1.7 to establish the effectiveness of the fire service.

$IF1.3$ factor is defined as follow:

$$IF1.3 = IF1.3.4 \times I_{SUPP} \tag{5.45}$$

where:

- $IF1.3.4$ is a Sub-Factor considering the maintenance of the suppression system;
- I_{SUPP} is a parameter composed by Sub-Factor $IF1.3.1$, $IF1.3.2$ and $IF1.3.3$.

I_{SUPP} is defined as follow:

$$I_{SUPP} = \lambda A_s + \alpha_T (1 - \lambda) P_{eq} \tag{5.46}$$

where:

- λ is the importance of the parameter A_s respect to the parameter P_{eq} and it depends on the type and the location of the system;
- $A_s = IF1.3.1$ is the Sub-Factor that takes into account the type and the location of the automatic system in the sector;
- $P_{eq} = IF1.3.2$ is the Sub-Factor that takes into account the portable equipment for fire suppression present in the sector.
- $\alpha_T = IF1.3.3$ is the Sub-Factor that takes into account the reliability of Fire Service Team.

Figure 5.13 shows the relationships between Factor $IF1.3$ and Sub-Factors $IF1.3.1$, $IF1.3.2$, $IF1.3.3$ and $IF1.3.4$.

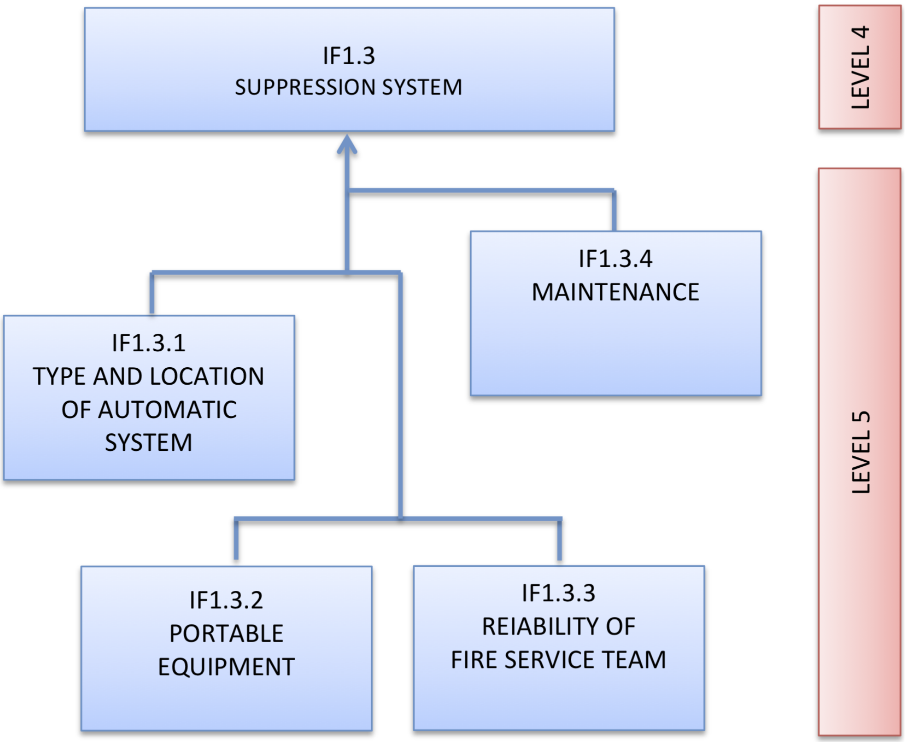


Figure 5.13: Relationships between Factor $IF1.3$ and Sub-Factors $IF1.3.1$, $IF1.3.2$, $IF1.3.3$ and $IF1.3.4$.

IF1.3.1

Cultural heritage objects (and off course Valuable Contents) are sensitive to damage by suppression systems. It is important to balance the system's quality in fire suppression with the preservation of the Valuable Contents that can be damaged by a wrong extinguishing substance. Sub-Factor $IF1.3.1$ can assume the values in Table 5.26.

IF1.3.2

This Sub-Factor check the presence and the distribution of portable suppression equipment. It is assumed that the portable equipment, where present, is suitable to extinguish fire in that room, according to the codes classification of extinguisher. Sub-Factor $IF1.3.2$ can assume the values in Table 5.27.

Automatic System			$IF1.3.1$
Location	Type	λ	
in rooms with highest fire load	no automatic system	0,00	7
	sprinkler	0,50	5
	gas system	0,35	4
	special system (i.e. watermist)	0,50	4
in rooms with valuable contents	no automatic system	0,00	7
	sprinkler	0,40	8
	gas system	0,65	3
	special system (i.e. watermist)	0,65	5
in the remaining parts of the sector	no automatic system	0,00	7
	sprinkler	0,50	8
	gas system	0,50	4
	special system (i.e. watermist)	0,50	3

Table 5.26: Risk indexes for $IF1.3.1$

Portable equipment	$IF1.3.2$
None	7
Extinguishing eq. NOT in every room	5
Extinguishing eq. in every room	3

Table 5.27: Risk indexes for $IF1.3.2$

IF1.3.3

Sub-Factor $IF1.3.3$ deals with the real reliability of the Fire Service Team. This because efficacy in extinguishing fire with portable equipments is strongly linked with the level of formation and training of the Fire Service Team. $IF1.3.3$ assumes values on the base of FSI (ref. paragraph 5.1.7) estimation. $IF1.3.3$ can assume the values in Table 5.28.

Reliability of Fire Protection Team	$IF1.3.3$
$FSI \leq 2$: Excellent	0,8
$2 < FSI \leq 3$: Very good	1,2
$3 < FSI \leq 4$: Law minimun compliance	1,5
$FSI > 4$: Not acceptable	2,0

Table 5.28: Values for $IF1.3.3$

IF1.3.4

Sub-Factor $IF1.3.4$ deals with the maintenance of portable and automatic suppression systems. Especially for portable equipment, a virtuous maintenance can be done by means of the Fire Service Team components. Duty of the historical building's manager is to organize internal audit for fire suppression system maintenance. $IF1.3.4$ can assume the values in Table 5.29.

Periodicity of maintenance	$IF1.3.4$
once a year	1,2
twice a year	1,0
Fire Service Team audit	0,8

Table 5.29: Values for $IF1.3.4$

IF1.4 Alarm system

Emergency and alarm signs start the evacuation of occupants and in this way intervene mainly for the safety of people. They also contribute to more immediate salvage intervention of contents. Their efficiency is a function of the type, number and location of the signals. If the detection signal is directly (automatically) sent to a central dispatching centre (e.g. fire brigade or other) the rescue process can start earlier. Duty of the building's manager is to organize the rescue team taking agreement with fire brigade or private surveillance company. $IF1.4$ factor is defined as follow:

$$IF1.4 = IF1.4.3 \times I_{AL} \tag{5.47}$$

where:

- $IF1.4.3$ is a Sub-Factor considering the maintenance of the alarm system;
- I_{AL} is a parameter composed by Sub-Factor $IF1.4.1$ and $IF1.4.2$.

I_{AL} is defined as follow:

$$I_{AL} = \lambda T_{al} + (1 - \lambda) L_{al} \tag{5.48}$$

where:

- λ =0,4 is the importance of the parameter T_{al} with respect to the parameter L_{al};
- $T_{al} = IF1.4.1$ is the Sub-Factor that takes into account the type of the alarm system in the sector;
- $L_{al} = IF1.4.2$ is the Sub-Factor that takes into account the location of the alarm system.

Figure 5.14 shows the relationships between Factor $IF1.4$ and Sub-Factors $IF1.4.1$, $IF1.4.2$, $IF1.4.3$.

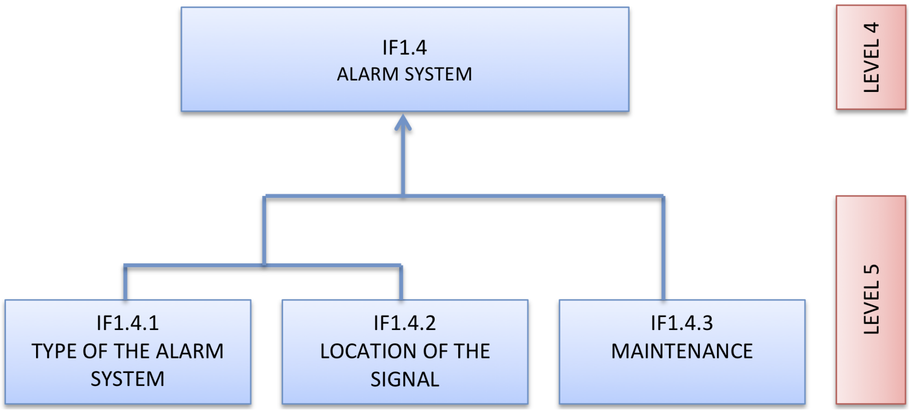


Figure 5.14: Relationships between Factor $IF1.4$ and Sub-Factors $IF1.4.1$, $IF1.4.2$, $IF1.4.3$.

IF1.4.1
Sub-Factor $IF1.4.1$ can assume the values in Table 5.30.

Type of Alarm System		$IF1.4.1$
Sound signal	Light signal	
no	no	9
	yes	8
alarm bell	no	4
	yes	4
spoken signal	no	1
	yes	1

Table 5.30: Risk indexes for $IF1.4.1$

IF1.4.2
Sub-Factor $IF1.4.2$ can assume the values in Table 5.31.

Location of the signal	$IF1.4.2$
signal only in the room/compartment	4
signal sent manually at the whole building	3

Table 5.31: Risk indexes for $IF1.4.2$

IF1.4.3

Sub-Factor $IF1.4.3$ can assume the values in Table 5.32.

Periodicity of maintenance	$IF1.4.3$
once a year	1,5
twice a year	1,0

Table 5.32: Values for $IF1.4.3$

IF2.1 Type of evacuation routes

Stairs, windows and balconies can be considered as evacuation routes. Since stairs lead people through internal evacuation routes and windows and balconies lead mainly contents to fire brigade rescue, two different categories are created: (i) internal connections and (ii) external evacuation routes. $IF2.1$ factor is defined as follow:

$$IF2.1 = IF2.1.3 \times I_{TY} \tag{5.49}$$

where:

- $IF2.1.3$ is a Sub-Factor considering if the escape route functions as an escape route for Valuable Contents;
- I_{TY} is a parameter composed by Sub-Factor $IF2.1.1$ and $IF2.1.2$.

I_{TY} is defined as follow:

$$I_{TY} = \lambda E_{ext} + (1 - \lambda)E_{int} \tag{5.50}$$

where:

- λ =0,3 is the importance of the parameter T_{al} respect to the parameter L_{al};
- $E_{ext} = IF2.1.1$ is the Sub-Factor that takes into account the type of external evacuation routes in the sector;
- $E_{int} = IF2.1.2$ is the Sub-Factor that takes into account the type of internal evacuation routes in the sector.

If more than a combination of the Sub-Factors is suitable to the sector, the worst grade is assigned.

Figure 5.15 shows the relationships between Factor $IF2.1$ and Sub-Factors $IF2.1.1$, $IF2.1.2$, $IF2.1.3$.

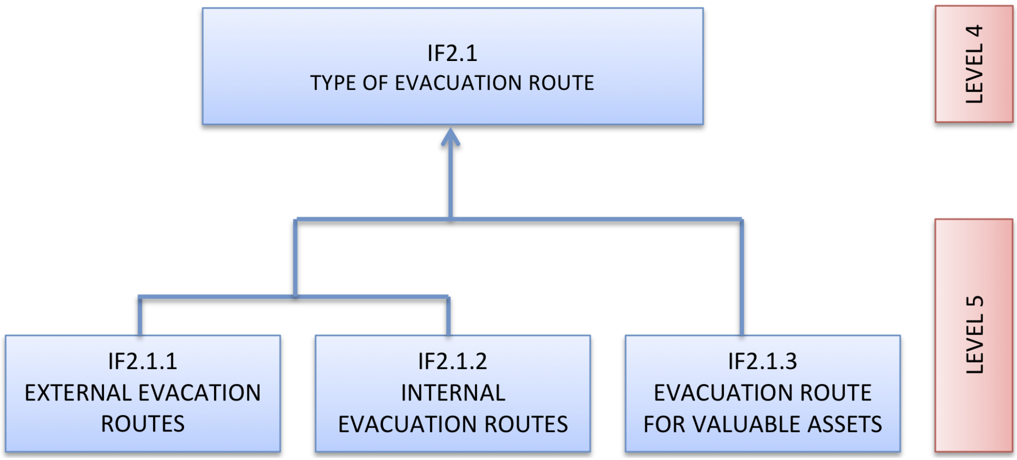


Figure 5.15: Relationships between $IF2.1$ and Sub-Factors $IF2.1.1$, $IF2.1.2$, $IF2.1.3$.

IF2.1.1

For evacuation of the Valuable Contents it is very important to put them in a safe place: if there are windows at the ground floor, even not trained people can intervene in damage limitation actions. If there is a "safe" balcony (according to Italian law DM 30/11/1983 [4] "safe" is more than 3,5x3,5m) into which evacuate, it is important to know how it is possible to reach that place (with a permanent external stair or with a Fire Brigade's ladder). Sub-Factor $IF2.1.1$ can assume the values in Table 5.33.

IF2.1.2

For evacuation of Valuable Contents is very important to have the possibility to put them in a safe fire compartment at the same floor. To make the Valuable Contents pass through stairs, even if protected, can represent a factor influencing the evacuation time; the best possible situation is putting contents in the nearest safe compartment at the same floor. Sub-Factor $IF2.1.2$ can assume the values in Table 5.34.

IF2.1.3

Sub-Factor $IF2.1.3$ considers if the escape route functions as an escape route for Valuable Contents. In case the route needs to function as evacuation routes for cultural heritage contents (e.g. in a salvage or damage limitation plan), the route needs to be evaluated in this respect. It is here proposed to increase the risk index substantially in function of the importance of the artworks that need to be evacuated. We refer in this dissertation to the ranking proposed in COST ACTION C17 [86]. According to COST C17, in developing a Damage Limitation Plan, a system of categorisation should be established to ensure that clear priorities exist for object removal. This should identify:

- **First priority**: items of international heritage value which are intimately connected with the building or its previous occupants;
- **Second priority**: items of national value or which are important to explain the

Type	Number	Dimensions and characteristics	*External evacuation routes: windows and balconies*	$IF2.1.1$
Windows and balcony cannot be used as evacuation route	-	-		9
windows	1	not at ground floor		7
	1	at ground floor		5
	>1	not at ground floor		5
	>1	at ground floor		2
balconies	1	surface $\geq 3,5m \times 3,5m$	reachable with a permanent stair	3
	1	surface $\geq 3,5m \times 3,5m$	reachable with a Fire Brigade ladder	4
	1	surface $< 3,5m \times 3,5m$	reachable with a permanent stair	5
	1	surface $< 3,5m \times 3,5m$	reachable with a Fire Brigade ladder	6
	>1	surface $\geq 3,5m \times 3,5m$	reachable with a permanent stair	2
	>1	surface $\geq 3,5m \times 3,5m$	reachable with a Fire Brigade ladder	3
	>1	surface $< 3,5m \times 3,5m$	reachable with a permanent stair	4
	>1	surface $< 3,5m \times 3,5m$	reachable with a Fire Brigade ladder	5

Table 5.33: Risk indexes for $IF2.1.1$

Staircases and internal connections	$IF2.1.2$
One staircase may be used as an evacuation route	7
Escape route leading to two independent staircases	5
Direct escape to two independent staircases	4
Direct communication with at least one safe fire compartment at the same floor	3

Table 5.34: Risk indexes for $IF2.1.2$

history of the building or its occupants. This should also include items that have a high monetary value;

- **Third Priority**: items that would be difficult or expensive to replace and which contribute to the history of the building;
- **Unclassified**: items that will be left in place.

Duty of the building's manager is to establish damage limitation plan for the Valuable Contents. This implies to understand which routes have to be used for contents evacuation. Sub-Factor $IF2.1.3$ can assume the values in Table 5.35.

Importance of the work of art to be evacuated	$IF2.1.3$
Unclassified: items that will be left in place	1,0
Third Priority: items that would be difficult or expensive to replace and which contribute to the history of the building	1,1
Second priority: items of national value or which are important in order to explain the history of the building or its occupants. This should also include items that have a high monetary value	1,3
First priority: items of international heritage value which are intimately connected with the building or its previous occupants	1,5

Table 5.35: Values for $IF2.1.3$

IF2.2 Dimensions and layout

In this Factor the following parameters are considered:

- $D = IF2.2.1$ that is the maximum travel distance to reach a safe place according to italian law DM 10/03/1998;
- $NF = IF2.2.2$ that is the number of floors to walk;
- $NS = IF2.2.3$ that is the number of sectors connected to the escape route.

Limits for walking distance are chosen according to italian law DM 10/03/1998 [9]; maximum number of floors to walk (up or down) is chosen according to Table 5.10. If the vertical connection is protected, it could be an advantage to have a big number of sector connected. On the contrary, if the vertical connection is not protected the more are the connected sector the worst is the situation.

Figure 5.16 shows the relationships between Factor $IF2.2$ and Sub-Factors $IF2.2.1$, $IF2.2.2$, and $IF2.2.3$.

Factor $IF2.2$ can assume the values in Table 5.36.

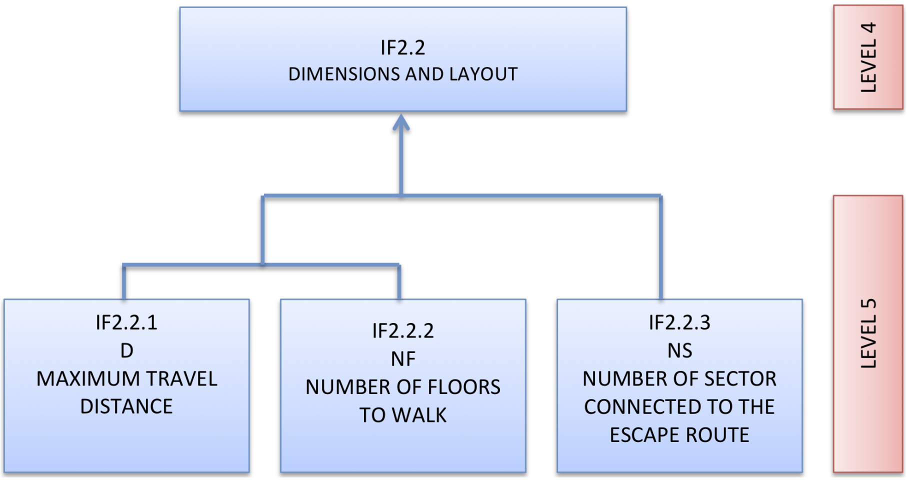


Figure 5.16: Relationships between Factor $IF2.2$ and Sub-Factors $IF2.2.1$, $IF2.2.2$, and $IF2.2.3$.

$IF2.2.1$ *Maximum travel distance*	$IF2.2.2$ *Number of floors to walk*	$IF2.2.3$ *Number of sectors connected*			
		Not protected stair		Protected stair	
		$NS > 4$	$NS \leq 4$	$NS > 4$	$NS \leq 4$
$30m \leq D$	$NF > 3$	9,0	7,0	3,0	3,0
	$NF \leq 3$	5,5	5,5	1,0	2,0
$15m \leq D < 30m$	$NF > 3$	3,6	3,6	3,0	3,0
	$NF \leq 3$	2,0	2,0	1,0	2,0
$15m > D$	$NF > 3$	2,0	2,0	2,0	2,0
	$NF \leq 3$	1,0	1,0	1,0	1,0

Table 5.36: Risk indexes for $IF2.2$

IF2.3 Linings and floorings

Reaction to fire is evaluated against the probability that flash-over may occur in critical spaces as escape routes. The grade for this Sub-Factor can be attributed on basis of the reaction to fire class of large surfaces, i.e. walls and ceiling linings. The worst class product occupying over 20% of the walls, or 20% of the ceiling is considered dominant for the attribution of the grade. The grade is linked with the potential contribution of the product to flash-over in an escape route and it is linked to product's Euroclass classification.

Sub-Factor $IF2.3.1$ is completely coincident with Factor $IF2.3$, that can assume the values in Table 5.37.

*E*uroclass classification		$IF2.3$
No flash-over	Stone, concrete, gypsum boards (A1-A2)	2,0
No or limited contribution to flash-over	Best FR woods impregnated, thick gypsum boards (B)	4,0
No flash-over within 10min	Textile wall cover on gypsum board (C)	5,5
Flash-over within 10min	Wood untreated (D)	7,0
Flash over with two minutes	Some plastics (E/F)	9,0

Table 5.37: Risk indexes for $IF2.3$

IF3.1 Vertical Structure

Vertical Structure is the structure composing the walls or columns of the analysed sector. The grade is linked with the resistance capacity that materials can assure. The worst type of structure occupying over 20% of the total is considered dominant for the attribution of the grade.

Sub-Factor $IF3.1.1$ is completely coincident with Factor $IF3.1$, that can assume values in Table 5.38.

Type of structure	$IF3.1$
Stone, concrete	3
Wood	8
Steel	7
Protected wood	3
Protected steel	3

Table 5.38: Risk indexes for $IF3.1$

IF3.2 Horizontal Structure

Horizontal Structure is the structure composing the floors you walk on in the sector. The grade, as for Factor $IF3.1$, is linked with the resistance capacity that materials can assure. The worst type of structure occupying over 20% of the total surface is considered dominant for the attribution of the grade.

Sub-Factor $IF3.2.1$ is completely coincident with Factor $IF3.2$, that can assume values in Table 5.39.

5.1.7 Extra Factor: Fire Service Index

This Extra Factor (FSI) is defined for the whole building. An efficient and reliable internal fire service is fundamental for the prevention and protection of the building and Valuable Contents. All buildings containing a working activity, according to the Italian fire code DM 10/03/1998 [9], must have an internal fire service. Setting a fire service is often just

Type of structure	$IF3.1$
Stone, concrete	3
Wood	7
Steel	7
Protected wood	3
Protected steel	3

Table 5.39: Risk indexes for $IF3.2$

a duty of the building's manager and the efficiency of the service is not guaranteed.

We want here to check the effectiveness of the fire service taking into account:

- FSI_1 *number of members* with respect to the total number of the sectors.
  It is important to organise the working turns to have always almost one person trained for each sector.

- FSI_2 *level of formation.*
  Specific theoretical and practical formation in fire prevention. According to Italian DM 10/03/1998 3 levels of fire prevention formation are defined.

- FSI_3 *frequency of retraining activities.*
  No fixed periodicity in retraining is established by the code; the more frequent is the training, the more reliable will be the activity of the fire service.

FSI is defined as follow:

$$FSI = \frac{FSI_1 + FSI_2 + FSI_3}{3} \tag{5.51}$$

$\underline{FSI_1}$

Number of Fire Service members is checked for each sector.
FSI_1 is defined as follow:

$$FSI = \frac{\sum_{i=1}^{n} IS_i}{n} \tag{5.52}$$

where:

- IS_i is the index assigned to each sector i;

- n is the total number of sectors.

For each sector IS_i indexes are assigned as in Table 5.40.

Number of members in the sector	IS_i
> 1	0
1	3
0	8

Table 5.40: Values for IS_i

$\underline{FSI_2}$
Level of formation is defined as is the Italian DM 10/03/1998. According to such law, the minimum content of training courses for components of fire prevention, fire fighting and emergency management in case of fire, must be related to the type of activity and the level of risk of fire of them and to the specific tasks assigned to workers. Taking into account the above criteria, in the code is reported a list of activities being viewed in the levels of high risk, medium and low as well as content and minimum durations of training courses related to them. The three levels are classified as follow:

- A: course for fire fighting staff for low risk of fire activities (4 hours duration);
- B: course for fire fighting staff for medium risk of fire activities (8 hours duration);
- C: course for fire fighting staff for high risk of fire activities (16 hours duration).

For the whole fire team FSI_2 index is assigned as in Table 5.41.

Level of formation	FSI_2
A: low fire risk	6
B: medium fire risk	3
C: high fire risk	1

Table 5.41: Values for FSI_2

$\underline{FSI_3}$
Retraining is defined basing the judgment on the type of the retraining (theoretical and/or practical) and on the periodicity (every year, every two years, etc.). In Italy there is no compulsory periodicity in retraining for Fire Service Team. For the whole fire team FSI_3 index is assigned as in Table 5.42.

Periodicity	*Type of retrainig*		
	Theoretical and practical	Only practical	Only theoretical
every year	1	2	3
every two years	4	5	6
every three years	7	8	9

Table 5.42: Values for FSI_3

Once calculated FSI, it is possible to enter in Table 5.28 to estimate Fire Service Team reliability.

5.2 Delphi Method

The Delphi method belongs to the subjective-intuitive methods of foresight.

Delphi was developed in the 1950's by the Rand Corporation, Santa Monica, California, in operations research [48, 61, 76]. The name can be traced back to the Delphic oracle; the name "Delphi" was intentionally coined by Kaplan, an associate professor of philosophy at the UCLA working for the RAND corporation, in a research effort directed at improving the use of expert predictions in policy-making. In Delphi's literature [83] it is underlined how in any scientific technique, theory, or hypothesis there are always some philosophical basis or theories about the nature of the world upon which that technique, theory, or hypothesis fundamentally rests or depends. Furthermore, in Delphi method, what that is the reality we construct as a product of Delphi interaction, assumes great importance. In [107] it is said that reality is a name we give our collections of tacit assumptions about what it is. We bring along these realities to give meaning to our interactions. Each of us maintains several of these realities but, since we need to construct the reality by Delphi design, the important thing is not how many different realities each of us has, but that one important product of each Delphi panel is the reality that is defined through its interaction.

5.2.1 Delphi Method theory

Delphi is therefore widely accepted as a tool in information systems research for identifying and prioritizing issues for managerial decision-making [89]. The Delphi method is based on structural surveys and makes use of the intuitive available information of the participants, who are mainly experts. Therefore, it delivers qualitative as well as quantitative results and has beneath its explorative, predictive even normative elements. There is not one Delphi methodology but there are several applications. There is an agreement that Delphi is an expert survey in two or more "rounds" in which in the second and later rounds of the survey the results of the previous round are given as feedback. Therefore, the experts answer from the second round on under the influence of their colleagues' opinions. Thus, the Delphi method is a *"relatively strongly structured group communication process, in which matters, on which naturally unsure and incomplete knowledge is available, are judged upon by experts"*, so the definition in [48].

In this dissertation Okoli and Pawlowski approach [89] in constructing a Delphi Method has been followed; Okoli and Pawlowski provide rigorous guidelines for the process of selecting appropriate experts for the study and give detailed principles for making design choices during the process that ensures a valid study. In Table 5.43 there is a resume of the Delphi criteria according to Okoli and Pawlowski.

Why Delphi Method in this research?
In light of Table 5.43, the Delphi method was selected for the following reasons:

1. This study is an investigation of factors that would influence Valuable Contents risk in Historical Heritage Buildings in fire event. No statistical data are available on this topic; both each building we deal with and its contents are unique and

Criteria of Delphi Method	
Summary of procedure	All the questionnaire design issues of a survey also apply to a Delphi study. After the researchers design the questionnaire, they select an appropriate group of experts who are qualified to answer the questions. The researchers then administer the survey and analyze the responses. Next, they design another survey based on the responses to the first one and re-administers it, asking respondents to revise their original responses and/or answer other questions based on group feedback from the first survey. The researchers reiterate this process until the respondents reach a satisfactory degree of consensus. The respondents are kept anonymous to each other (though not to the researcher) throughout the process.
Representativeness of sample	The questions that a Delphi study investigates are those of high uncertainty and speculation. Thus, a general population, or even a narrow subset of a general population, might not be sufficiently knowledgeable to answer the questions accurately. **A Delphi study is a virtual panel of experts gathered to arrive at an answer from a difficult question.** Thus, a Delphi study could be considered a type of virtual meeting or as a group decision technique, though it appears to be a complicated survey.
Sample size for statistical power and significant findings	The Delphi group size does not depend on statistical power, but rather on group dynamics for arriving at consensus among experts. Thus, the literature recommends 10 - 18 experts on a Delphi panel.
Individual vs. group response	Studies have consistently shown that for questions requiring expert judgment, the average of individual responses is inferior to the averages produced by group decision processes; research has explicitly shown that the Delphi method bears this out.
Reliability and response revision	Pretesting is also an important reliability assurance for the Delphi method. However, test-retest reliability is not relevant, since researchers expect respondents to revise their responses.
Construct validity	In addition to what is required of a survey, the Delphi method can employ further construct validation by asking experts to validate the researcher's interpretation and categorization of the variables. The fact that Delphi is not anonymous (to the researcher) permits this validation step, unlike many surveys.
Anonymity	Respondents are always anonymous to each other, but never anonymous to the researcher. This gives the researchers much opportunity to follow up for clarifications and further qualitative data.
Non-response issues	Non-response is typically very low in Delphi surveys, since most researchers have personally obtained assurances of participation.
Attrition effects	Similar to non-response, attrition tends to be low in Delphi studies, and the researchers usually can easily ascertain the cause by talking with the dropouts.
Richness of data	In addition to the richness issues of traditional surveys, Delphi studies inherently provide richer data because of their multiple iterations and their response revision due to feedback. Moreover, Delphi participants tend to be open to follow-up interviews.

Table 5.43: Criteria of Delphi Method, elaboration from [89].

statistical data have no sense. This complex issue requires knowledge from people who understand and manage the specific topic form different viewpoints. Thus, a Delphi study answers the study questions more appropriately.

2. A panel study most appropriately answers the research questions, rather than any individual expert's responses. Delphi is an appropriate group method. Among other high-performing group decision analysis methods, Delphi is desirable in that it does not require the experts to meet physically.

3. Although there may be a relatively limited number of experts with knowledge about the research questions, the Delphi panel size requirements are modest, and it would be practical to solicit up to three panels from 10 members in size.

4. The Delphi study is flexible in its design, and amenable to follow-up interviews. This permits the collection of richer data to lead to a deeper understanding of the fundamental research questions.

5. We select the procedure for conducting Delphi studies outlined by Okoli and Pawlowski (based on Schmidt outline) for the study because it would serve the dual purpose of soliciting opinions from experts and having them ranked according to their importance.

Delphi Organization
One of the most critical requirements is the selection of qualified experts. We divided experts into panels; three relevant categories of experts have important and valuable knowledge about fire risk management in historical buildings:

1. *academics* (identified with the AC abbreviation);

2. *technicians and practitioner working in management of historical buildings* (identified with the EC abbreviation);

3. *fire brigades* (identified with the VF abbreviation).

These groups probably would have somewhat different perspectives. Since it is a goal to obtain a reasonable degree of consensus, it would be best to have panels that separate these groups. This design also permits comparisons of the perspectives of the different stakeholder groups. Following recommendations from Delphi literature, there will be 10 people in each panel. This structure will obtain a sufficient number of perspectives from the "inside", and we could perform analyses to see if there are differences in perspectives between respondents inside and outside.

The choice is to populate the panels with experts having a common background with respect to the research topic; such common background was identified in the regional origin of the members. Since we deal with unique heritage buildings and works of art, managing them in a country like Italy is quite different from managing them in the remanent part of the world (Europe included) due to a of different factors, first of which is the typology of historical buildings that is strictly linked with the history and culture of the place they stand. To make the answers from experts the most reliable as possible, only Italian experts (and in particular experts with experience in Tuscan buildings heritage) have been chosen. The experts' judgments have this way an high degree of reliability in the Tuscan context and they can be easily extended to Italy, while it is almost impossible to expand the judgments to the remaining parts of Europe and completely impossible to fit them to the rest of the world.

The Web, e-mail and phone were the means of contacting the experts. The objective was to contact people in different organizations who are experts themselves, and who can provide additional contacts within and outside their own organizations. Each category of experts required a different approach for identifying experts:

1. *Academics*: this list was populated almost entirely via an experts' survey in "Universitá degli Studi di Firenze"; mainly contacting professors and researchers belonging to the DICEA department (Dipartimento di Ingegneria Civile e Ambientale) of the Faculty of Engineering;

2. *Technicians and practitioners working in historical building management*: this list was populated contacting a technician working in *Opificio delle Pietre Dure* in Florence, one of the most important conservation laboratories in Europe. Thanks to his helpfulness it was possible to write down a list of practitioners and technicians that operate daily on Tuscan heritage buildings containing Art History Masterpieces;

3. *Fire brigades*: this list was populated contacting the executive officer of the fire brigade command in Siena. The executive officer is one of the most important experts in fire prevention in historical heritage buildings; thanks to him it was possible to contact experts belonging to the fire brigade command in Florence that took part to the Delphi.

Furthermore, to insert people in the panels, we needed to obtain basic biographical information for every expert on the list in order to determine what qualifications they possess to make them experts (for example, the number of papers published and presentations made, the length of years of practice, professional positions - mainly for academics and fire brigades).

We contacted each panelist and explained the subject of the study and the procedures required for it, including the commitment required. For this study, we asked panelists to commit to complete up to six 8-10 min questionnaires and returning them within the shortest time possible of receipt, for a total of two hours over a period of 2-3 months. We imposed a limit of six short questionnaires so as not to tax the participants, and yet give them an honest appraisal of their time commitment.

To make the survey more slender, a preliminary explanation of the research and a"user guide" to give judgments were sent to each expert. Data collection was then conducted personally by the researcher in a specific meeting arranged with each one of the experts. To meet personally, each expert made them more confident with the method and with the aim of the research, increasing this way the reliability of judgments.

The administration of the questionnaires followed the procedure for "ranking-type" Delphi studies outlined in [89]. This involved three general steps: (*i*) discussion about important factors; (*ii*) narrowing down the original list to the most important ones; and (*iii*) ranking the list of important factors.

In the first step Experts expressed their judgment about the Factors composing the Characteristics, stating if, in their opinion, Factors were influent and/or coherent with the aim of the research. From this first step the majority of experts considered to neglect some Factors; it is important to underline that factors neglected by the experts have been then comprehended in the sensitivity analysis performed on the Analytical Structure (ref. paragraph 5.2.4). Basing on the sensitivity analysis results performed after Delphi's first round, exactly the Factors neglected by the experts have been cut off from the structure.

Then judgments regarding weights of the six Characteristics with respect to the three Objectives were collected. To each one of the experts was asked to give judgments in pairs comparison according to the scale of importance in Table 5.1.

Each expert had to rank the Characteristics (both External and Internal) with respect to each Objectives composing a Saaty Matrix; control of Consistency Index has been performed for each one of the matrix in order to have always $C.R. < 10\%$.

The goal of this phase is to reach a consensus in the ranking of the relevant factors within each panel. Studies have consistently found that it is more difficult to reach consensus with Delphi groups than with ones that involve direct interaction between participants. However, with a panel design it is less difficult to obtain consensus because the researchers deliberately select panel members for their homogeneity.

This phase of the procedure involved each panel separately ranking the characteristics; each ranked list will reflect the priority order for the specific panel. In this phase, each expert individually submitted a rank ordering of the items.

When it comes to quantitatively determine the ranks of the items in the lists, literature provides an excellent and detailed guideline of the principles to follow. There is a number of different metrics for measuring non-parametric rankings, but Kendall's W coefficient of concordance is widely recognized as the best one [89].

According to Kendall definition [70], suppose that object i is given the rank $r_{i,j}$ by judge number j, where there are in total n objects and m judges. Then the total rank given to object i is

$$R_i = \sum_{j=1}^{m} r_{i,j}, \tag{5.53}$$

and the mean value of these total ranks is

$$\overline{R} = \frac{1}{2}m(n+1). \tag{5.54}$$

The sum of squared deviations, S, is defined as

$$S = \sum_{i=1}^{n} (R_i - \overline{R})^2, \tag{5.55}$$

and then Kendall's W is defined as

$$W = \frac{12S}{m^2(n^3 - n)}. \tag{5.56}$$

If the test statistic W is 1, then all the judges or survey respondents have been unanimous, and each judge or respondent has assigned the same order to the list of objects or concerns. If W is 0, then there is no overall trend of agreement among the respondents, and their responses may be regarded as essentially random. Intermediate values of W indicate a greater or lesser degree of unanimity among the various judges or respondents. Legendre [75] discusses a variant of the W statistic which accommodates ties in the rankings, if a lot of ties are present.

The value of W ranges from 0 to 1, with 0 indicating no consensus, and 1 indicating perfect consensus between lists. Literature provides interpretations of the different values of W, with 0,7 indicating strong agreement. After calculating the concordance within each panel, the W value suggests how to proceed in the ranking.

A W value of 0,7 or greater would indicate satisfactory agreement, and we would consider the ranking phase completed. However, if W is less than 0,7, the ranking questionnaire must be resent to the members of that panel. Each reiteration would return the items for the panel, listed in order of mean ranks.

For each item, we gave the panelists the following information to help them to revise their rankings:

- the mean rank of the item for the panel;
- the panelist's ranking of the item in the former round;
- an indication of the current level of consensus, based on the value of W.

Based on this, we asked the panelists to revise their rankings for each item, again asking them to explain their rankings and revisions.

Mean rank for each panel has been calculated according to Saaty [104]; when a group uses the AHP, their judgments can be combined after discussion by applying the geometric mean to the judgments which derives from the requirement. For each panel we built a six "3×3" Saaty matrix (three matrix with weights of the External Characteristics with respect to the Objectives and three matrix with weights of the Internal Characteristics with respect to the Objectives):

$$B = \begin{pmatrix} b_{11} & b_{12} & b_{13} \\ b_{21} & b_{22} & b_{23} \\ b_{31} & b_{32} & b_{33} \end{pmatrix} \tag{5.57}$$

were each b_{ij} element is

$$b_{ij} = (a_{1,ij} \cdot a_{2,ij} \cdot \ldots \cdot a_{k,ij})^{\frac{1}{k}} \tag{5.58}$$

with k number of participants giving a_{ij} judgments. In our Delphi $k = 10$ for each panel.

The ranking process has to be reiterated until one of two stopping criteria is reached:

1. W reaches a value of 0,7, indicating a satisfactory level of concordance;

2. the mean ranking for two successive rounds is not significantly different.

At the end of this ranking phase, we will have eighteen ranked lists - six from each of the panels - representing the priorities that each panels placed on the Characteristics with respect to the Objectives. This rigorous process assures that the Characteristics rankings are a valid indicator of the relative importance of the various element.

Since we have three panels, at the end of the Delphi process we built six matrixes (three for the External Characteristics and three for the Internal Characteristics) containing the mean judgments from the three panels. The components of such matrixes are the final values that we put inside the risk assessment method as weights of the Characteristics with respect to the Objectives.

In next paragraphs there is a sum of the results from Delphi's rounds.

5.2.2 Delphi's first round

Results from the first round are expected to be the base onto which building consensus among the experts with judgments expressed in the second round. In the first round, each expert had to become confident with the research topic and the AHP structure. As said, all the judgments have been collected by a personal meeting with each expert to whom was fully explained the research they took part into. Once illustrated the relations among Factors and Characteristics, each expert gave his judgments in pairwise comparisons among the Characteristics with respect to the Objectives. For each matrix it was $C.R. < 10\%$. Judgments composed Saaty matrixes of which main eigenvector was calculated to extract the Characteristics ranking. According to equation 5.57, a mean matrix has been built and its main eigenvector is the ranking of the panel.

Data from the first round were gathered in graphs and tables easy to be read in order to present such data to the experts before the second round. For each panel graphs showing the distribution of judgments for each Characteristic with respect to the Objectives were plot.

In the following sections the ranking results of for each Objective and for each panel are shown. For each table $C.R.$ and W are reported.

To each table is associated a graph showing the mean ranking for the panel in first Delphi round.

5.2.2.1 Panel 1: academics

External Characteristics with respect to Objective 1 (Evacuation).
Results are shown in Table 5.44 and Figure 5.17.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
AC01	66%	25%	9%
AC02	11%	78%	11%
AC03	15%	55%	30%
AC04	10%	74%	16%
AC05	24%	68%	8%
AC06	67%	10%	23%
AC07	12%	65%	23%
AC08	43%	43%	14%
AC09	20%	71%	9%
AC10	16%	74%	10%
Combined	26%	58%	16%
Rank	2	1	3

Table 5.44: External Characteristics with respect to Objective 1 - Panel 1; $C.R. = 0,01\%$ and $W = 0,4$.

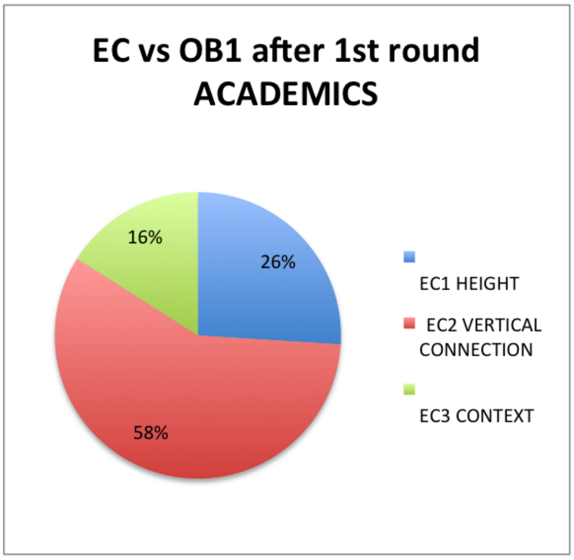


Figure 5.17: External Characteristics with respect to Objective 1: mean ranking from Panel 1.

External Characteristics with respect to Objective 2 (Fire brigade effectiveness).
Results are shown in Table 5.45 and Figure 5.18.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
AC01	50%	29%	21%
AC02	23%	12%	65%
AC03	15%	30%	55%
AC04	11%	11%	78%
AC05	24%	9%	67%
AC06	24%	13%	63%
AC07	20%	25%	55%
AC08	33%	33%	33%
AC09	24%	9%	67%
AC10	68%	9%	23%
Combined	29%	17%	54%
Rank	2	3	1

Table 5.45: External Characteristics with respect to Objective 2 - Panel 1; $C.R. = 0,1\%$ and $W = 0,3$.

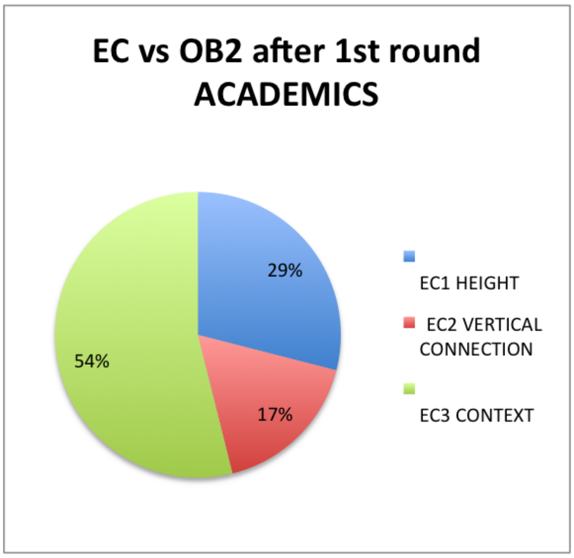


Figure 5.18: External Characteristics with respect to Objective 2: mean ranking from Panel 1.

External Characteristics with respect to Objective 3 (Fire and smoke spread).
Results are shown in Table 5.46 and Figure 5.19.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
AC01	20%	73%	7%
AC02	46%	47%	7%
AC03	50%	21%	29%
AC04	60%	20%	20%
AC05	7%	61%	32%
AC06	60%	25%	15%
AC07	16%	71%	13%
AC08	46%	47%	7%
AC09	20%	73%	7%
AC10	16%	71%	13%
Combined	33%	53%	14%
Rank	2	1	3

Table 5.46: External Characteristics with respect to Objective 3 - Panel 1; $C.R. = 0,4\%$ and $W = 0,4$.

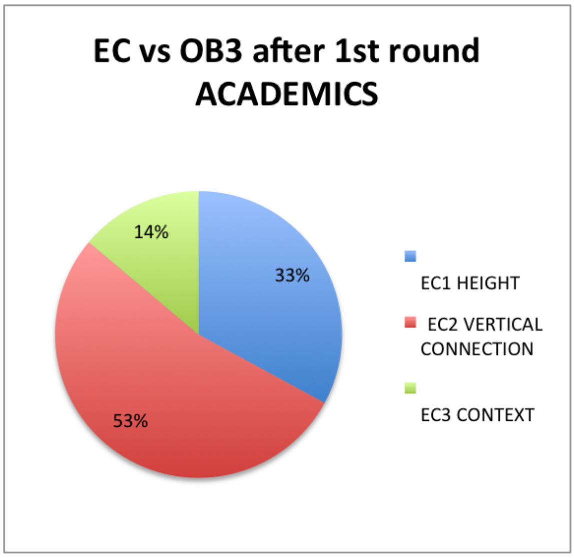


Figure 5.19: External Characteristics with respect to Objective 3: mean ranking from Panel 1.

Internal Characteristics with respect to Objective 1 (Evacuation).
Results are shown in Table 5.47 and Figure 5.20.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
AC01	17%	57%	26%
AC02	45%	47%	8%
AC03	24%	63%	13%
AC04	65%	23%	12%
AC05	12%	79%	8%
AC06	29%	50%	21%
AC07	13%	77%	10%
AC08	67%	21%	12%
AC09	9%	71%	20%
AC10	77%	13%	10%
Combined	33%	53%	14%
Rank	2	1	3

Table 5.47: Internal Characteristics with respect to Objective 1 - Panel 1; $C.R. = 0,5\%$ and $W = 0,5$.

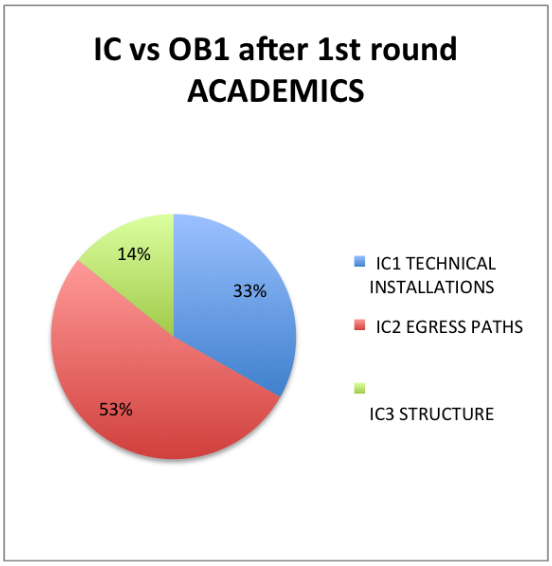


Figure 5.20: Internal Characteristics with respect to Objective 1: mean ranking from Panel 1.

Internal Characteristics with respect to Objective 2 (Fire brigade effectiveness).
Results are shown in Table 5.48 and Figure 5.21.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
AC01	40%	20%	40%
AC02	74%	10%	16%
AC03	20%	20%	60%
AC04	19%	9%	72%
AC05	20%	7%	73%
AC06	15%	54%	30%
AC07	30%	59%	11%
AC08	47%	43%	10%
AC09	67%	9%	24%
AC10	30%	54%	16%
Combined	41%	24%	35%
Rank	1	3	2

Table 5.48: Internal Characteristics with respect to Objective 2 - Panel 1; $C.R. = 0,1\%$ and $W = 0,1$.

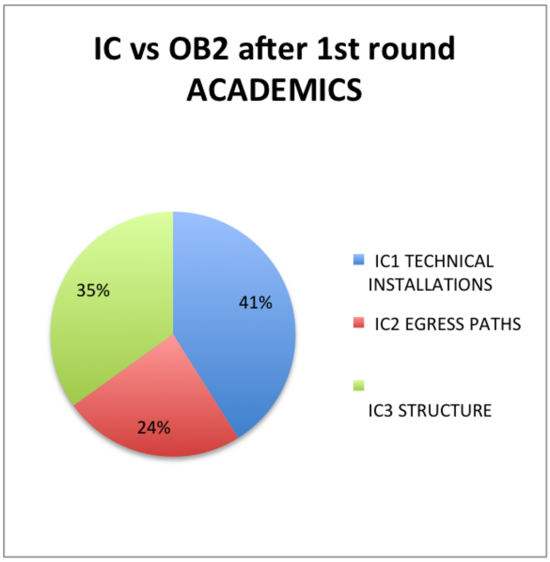


Figure 5.21: Internal Characteristics with respect to Objective 1: mean ranking from Panel 1.

Internal Characteristics with respect to Objective 3 (Fire and smoke spread).
Results are shown in Table 5.49 and Figure 5.22.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
AC01	61%	8%	31%
AC02	46%	46%	8%
AC03	25%	8%	67%
AC04	12%	69%	19%
AC05	77%	11%	12%
AC06	60%	15%	25%
AC07	57%	12%	31%
AC08	68%	9%	23%
AC09	50%	25%	25%
AC10	68%	8%	24%
Combined	55%	18%	27%
Rank	1	3	2

Table 5.49: Internal Characteristics with respect to Objective 3 - Panel 1; $C.R. = 0,01\%$ and $W = 0,3$.

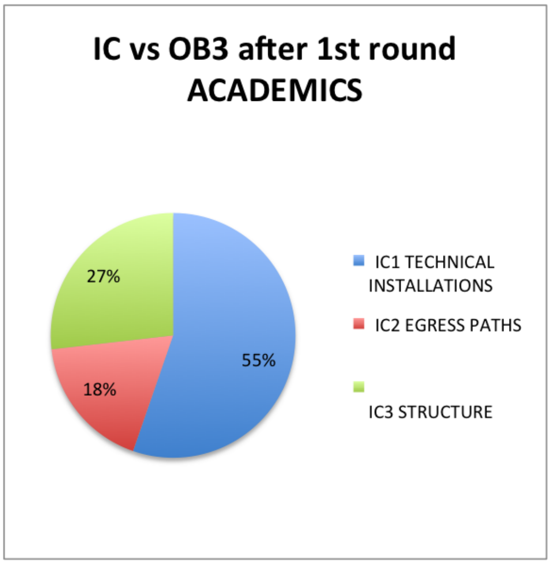


Figure 5.22: Internal Characteristics with respect to Objective 1: mean ranking from Panel 1.

5.2.2.2 Panel 2: technicians and practitioners

External Characteristics with respect to Objective 1 (Evacuation).
Results are shown in Table 5.50 and Figure 5.23.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
EC01	66%	25%	9%
EC02	7%	76%	17%
EC03	15%	55%	30%
EC04	43%	43%	14%
EC05	20%	71%	9%
EC06	20%	71%	9%
EC07	16%	74%	10%
EC08	13%	24%	63%
EC09	47%	47%	6%
EC10	26%	59%	15%
Combined	25%	60%	15%
Rank	2	1	3

Table 5.50: External Characteristics with respect to Objective 1 - Panel 2; $C.R. = 0,4\%$ and $W = 0,4$.

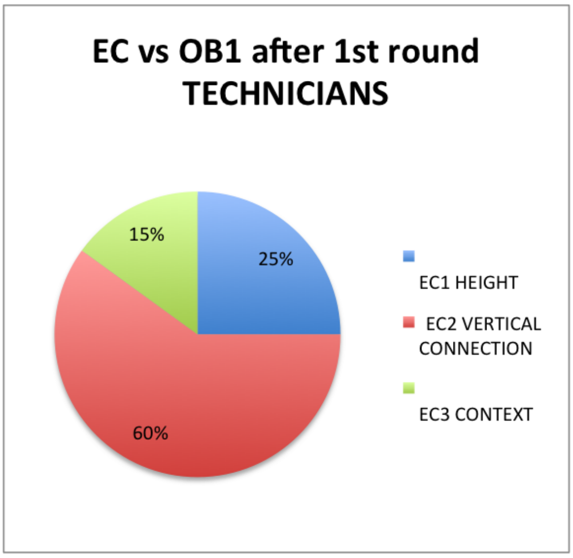


Figure 5.23: External Characteristics with respect to Objective 1: mean ranking from Panel 2.

External Characteristics with respect to Objective 2 (Fire brigade effectiveness).
Results are shown in Table 5.51 and Figure 5.24.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
EC01	50%	29%	21%
EC02	16%	10%	74%
EC03	16%	30%	54%
EC04	33%	33%	34%
EC05	24%	8%	68%
EC06	19%	73%	8%
EC07	68%	9%	23%
EC08	10%	31%	59%
EC09	15%	20%	65%
EC10	29%	26%	45%
Combined	29%	23%	48%
Rank	2	3	1

Table 5.51: External Characteristics with respect to Objective 2 - Panel 2; $C.R. = 0,3\%$ and $W = 0,1$.

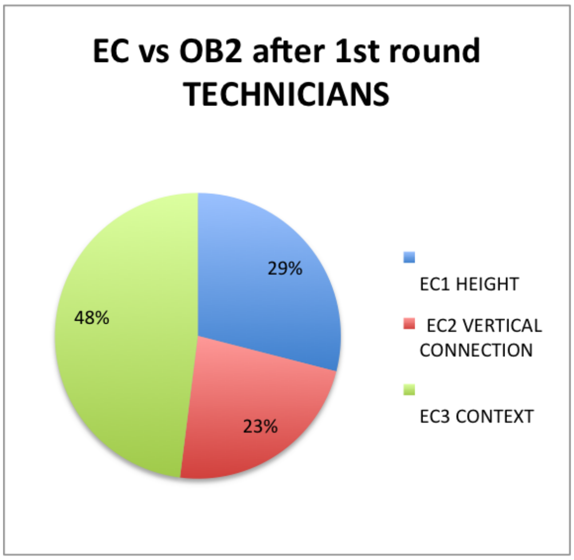


Figure 5.24: External Characteristics with respect to Objective 2: mean ranking from Panel 2.

External Characteristics with respect to Objective 3 (Fire and smoke spread).
Results are shown in Table 5.52 and Figure 5.25.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
EC01	20%	73%	7%
EC02	47%	47%	6%
EC03	6%	47%	47%
EC04	47%	47%	6%
EC05	20%	73%	7%
EC06	63%	22%	15%
EC07	16%	71%	13%
EC08	43%	40%	17%
EC09	9%	15%	76%
EC10	31%	49%	20%
Combined	30%	51%	19%
Rank	2	1	3

Table 5.52: External Characteristics with respect to Objective 3 - Panel 2; $C.R. = 1,2\%$ and $W = 0,4$.

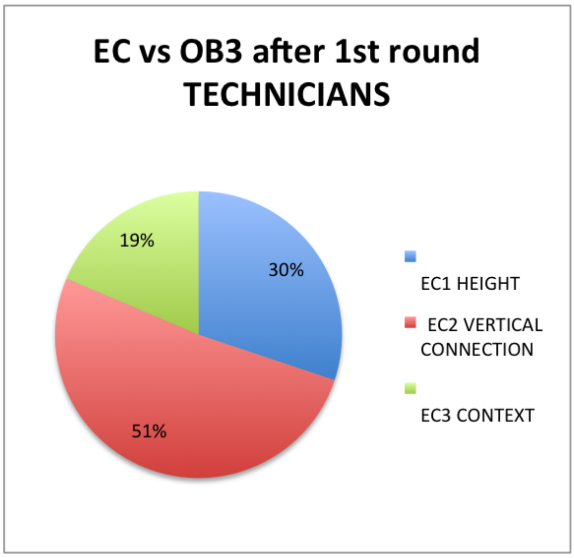


Figure 5.25: External Characteristics with respect to Objective 3: mean ranking from Panel 2.

Internal Characteristics with respect to Objective 1 (Evacuation).
Results are shown in Table 5.53 and Figure 5.26.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
EC01	17%	57%	26%
EC02	47%	47%	6%
EC03	24%	63%	13%
EC04	67%	21%	12%
EC05	9%	71%	20%
EC06	14%	32%	54%
EC07	77%	13%	10%
EC08	24%	63%	13%
EC09	12%	45%	43%
EC10	23%	64%	13%
Combined	29%	51%	20%
Rank	2	1	3

Table 5.53: Internal Characteristics with respect to Objective 1 - Panel 2; $C.R. = 1,2\%$ and $W = 0,3$.

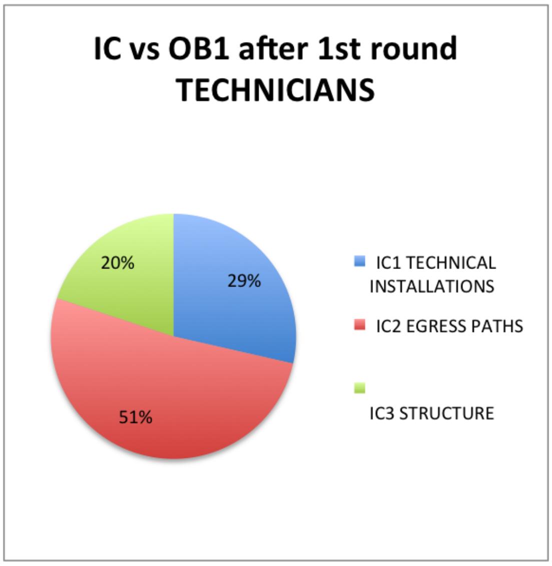


Figure 5.26: Internal Characteristics with respect to Objective 1: mean ranking from Panel 2.

Internal Characteristics with respect to Objective 2 (Fire brigade effectiveness).
Results are shown in Table 5.54 and Figure 5.27.

Partecipant	*IC1 technical installa-tions*	*IC2 egress paths*	*IC3 structure*
EC01	40%	20%	40%
EC02	47%	6%	47%
EC03	20%	20%	60%
EC04	47%	43%	10%
EC05	67%	9%	24%
EC06	13%	30%	57%
EC07	30%	55%	15%
EC08	63%	18%	19%
EC09	12%	45%	43%
EC10	63%	18%	19%
Combined	41%	25%	34%
Rank	1	3	2

Table 5.54: Internal Characteristics with respect to Objective 2 - Panel 2; $C.R. = 3\%$ and $W = 0,1$.

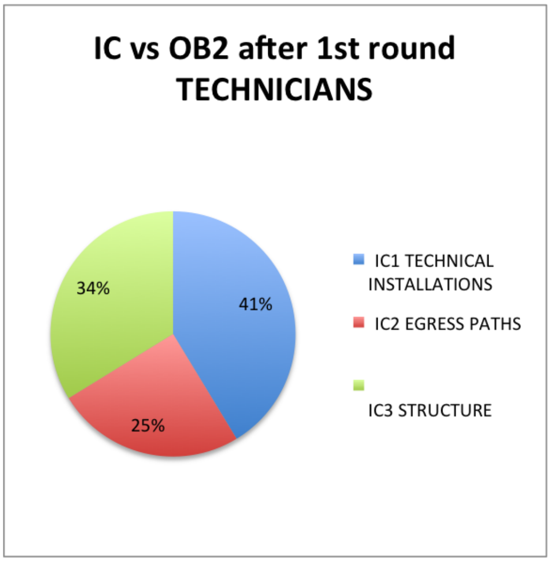


Figure 5.27: Internal Characteristics with respect to Objective 1: mean ranking from Panel 2.

Internal Characteristics with respect to Objective 3 (Fire and smoke spread).
Results are shown in Table 5.55 and Figure 5.28.

Partecipant	*IC1 technical installa-tions*	*IC2 egress paths*	*IC3 structure*
EC01	61%	8%	31%
EC02	68%	10%	22%
EC03	24%	9%	67%
EC04	68%	9%	23%
EC05	50%	25%	25%
EC06	71%	12%	17%
EC07	68%	8%	24%
EC08	73%	11%	16%
EC09	61%	8%	31%
EC10	50%	25%	25%
Combined	61%	11%	28%
Rank	1	3	2

Table 5.55: Internal Characteristics with respect to Objective 3 - Panel 2; $C.R. = 0,7\%$ and $W = 0,7$.

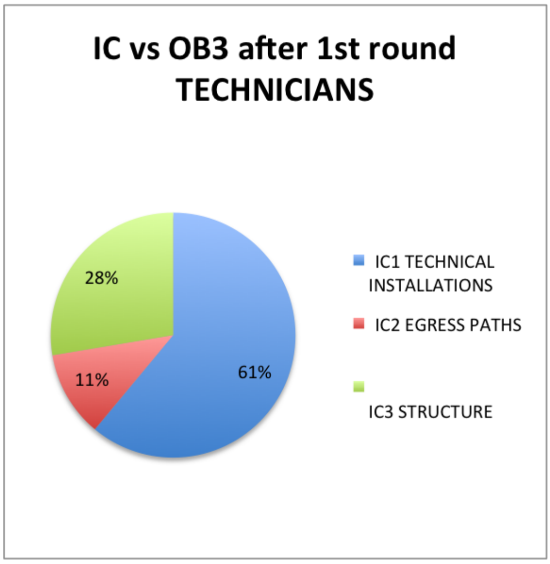


Figure 5.28: Internal Characteristics with respect to Objective 1: mean ranking from Panel 2.

5.2.2.3 Panel 3: fire brigades

External Characteristics with respect to Objective 1 (Evacuation).
Results are shown in Table 5.56 and Figure 5.29.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
VF01	16%	76%	8%
VF02	10%	66%	24%
VF03	69%	19%	12%
VF04	16%	76%	8%
VF05	35%	30%	35%
VF06	16%	13%	71%
VF07	16%	13%	71%
VF08	30%	35%	35%
VF09	14%	43%	43%
VF10	28%	42%	30%
Combined	28%	42%	30%
Rank	3	1	2

Table 5.56: External Characteristics with respect to Objective 1 - Panel 3; $C.R. = 0,3\%$ and $W = 0,1$.

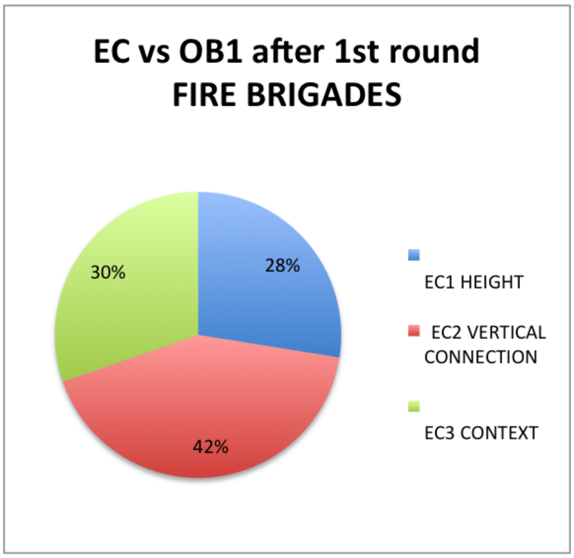


Figure 5.29: External Characteristics with respect to Objective 1: mean ranking from Panel 3.

External Characteristics with respect to Objective 2 (Fire brigade effectiveness).
Results are shown in Table 5.57 and Figure 5.30.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
VF01	16%	74%	10%
VF02	10%	24%	66%
VF03	20%	10%	70%
VF04	14%	74%	12%
VF05	47%	10%	43%
VF06	10%	31%	59%
VF07	10%	31%	59%
VF08	17%	60%	23%
VF09	65%	15%	20%
VF10	25%	44%	31%
Combined	25%	47%	28%
Rank	3	1	2

Table 5.57: External Characteristics with respect to Objective 2 - Panel 3; $C.R. = 1,5\%$ and $W = 0,1$.

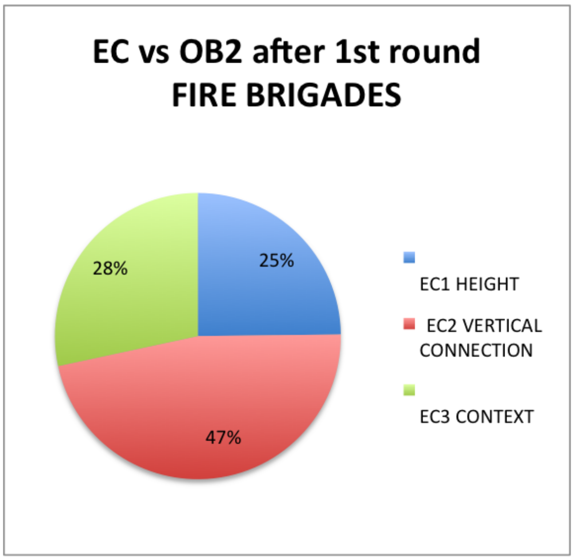


Figure 5.30: External Characteristics with respect to Objective 2: mean ranking from Panel 3.

External Characteristics with respect to Objective 3 (Fire and smoke spread).
Results are shown in Table 5.58 and Figure 5.31.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
VF01	10%	81%	9%
VF02	10%	81%	9%
VF03	14%	14%	72%
VF04	14%	78%	8%
VF05	12%	19%	69%
VF06	8%	60%	32%
VF07	8%	60%	32%
VF08	47%	47%	6%
VF09	20%	20%	60%
VF10	17%	55%	28%
Combined	17%	58%	25%
Rank	3	1	2

Table 5.58: External Characteristics with respect to Objective 3 - Panel 3; $C.R. = 1,4\%$ and $W = 0,3$.

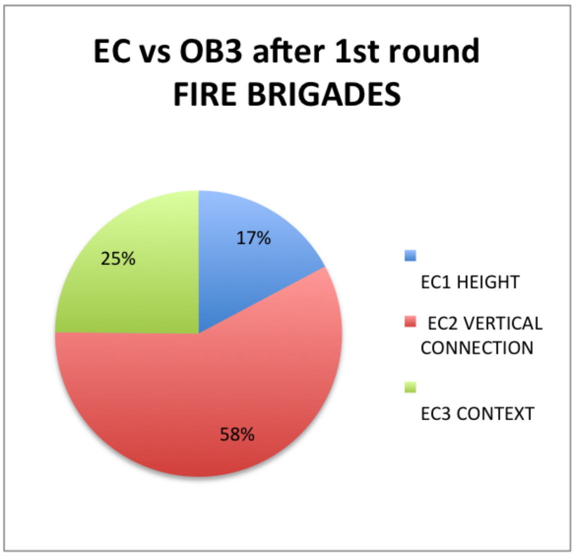


Figure 5.31: External Characteristics with respect to Objective 3: mean ranking from Panel 3.

Internal Characteristics with respect to Objective 1 (Evacuation).
Results are shown in Table 5.59 and Figure 5.32.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
VF01	12%	71%	17%
VF02	16%	71%	13%
VF03	10%	45%	45%
VF04	12%	69%	19%
VF05	22%	43%	35%
VF06	45%	15%	40%
VF07	45%	15%	40%
VF08	9%	67%	24%
VF09	12%	45%	43%
VF10	16%	71%	13%
Combined	18%	52%	30%
Rank	3	1	2

Table 5.59: Internal Characteristics with respect to Objective 1 - Panel 3; $C.R. = 1\%$ and $W = 0,3$.

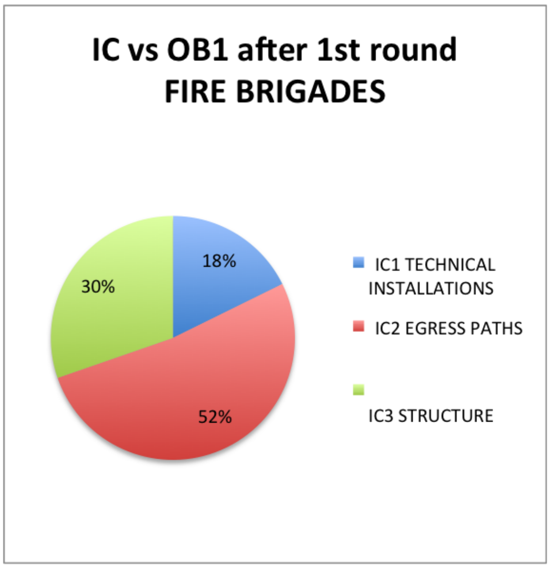


Figure 5.32: Internal Characteristics with respect to Objective 1: mean ranking from Panel 3.

Internal Characteristics with respect to Objective 2 (Fire brigade effectiveness).
Results are shown in Table 5.60 and Figure 5.33.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
VF01	8%	72%	20%
VF02	16%	71%	13%
VF03	23%	17%	60%
VF04	8%	72%	20%
VF05	60%	17%	23%
VF06	44%	12%	44%
VF07	44%	12%	44%
VF08	72%	20%	8%
VF09	24%	13%	63%
VF10	10%	71%	19%
Combined	30%	35%	35%
Rank	3	1	2

Table 5.60: Internal Characteristics with respect to Objective 2 - Panel 3; $C.R. = 0,9\%$ and $W = 0,1$.

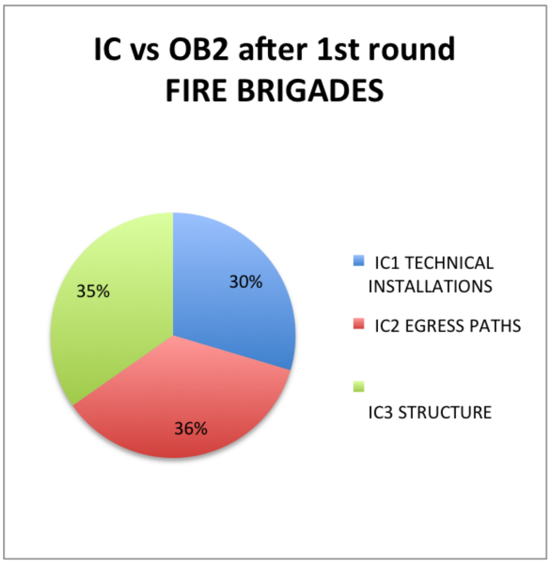


Figure 5.33: Internal Characteristics with respect to Objective 1: mean ranking from Panel 3.

Internal Characteristics with respect to Objective 3 (Fire and smoke spread).
Results are shown in Table 5.61 and Figure 5.34.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
VF01	11%	11%	78%
VF02	29%	50%	21%
VF03	10%	20%	70%
VF04	13%	12%	75%
VF05	10%	32%	58%
VF06	75%	8%	17%
VF07	75%	8%	17%
VF08	7%	73%	20%
VF09	35%	43%	22%
VF10	10%	10%	80%
Combined	25%	24%	51%
Rank	2	3	1

Table 5.61: Internal Characteristics with respect to Objective 3 - Panel 3; $C.R. = 0,4\%$ and $W = 0,1$.

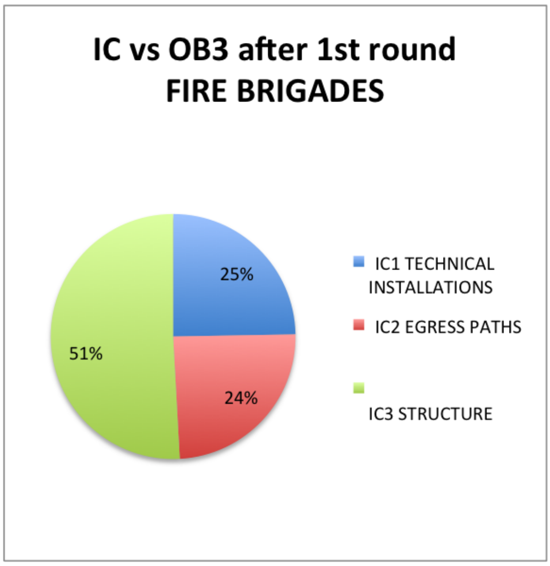


Figure 5.34: Internal Characteristics with respect to Objective 1: mean ranking from Panel 3.

5.2.2.4 Final ranking round 1

In this paragraph the mean judgments from each panel and the final mean of such values are shown. Concordance in aggregated mean from each panel is not requested; we don't check W coefficient in aggregated mean because Delphi has been performed referring the feedback to the judgments coming from each panel. Concordance among the panels is not the aim of the process: it is just requested that each panel gives reliable judgments with respect to its own experience and cultural background. Each panel can express reliable judgments because it is composed by experts sharing a common point of view on the topic. Not necessarily the three panels have to give back the same rankings. In this phase only C.R. is checked.

External Characteristics with respect to Objective 1 (Evacuation).
Results are shown in Table 5.62 and Figure 5.35.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
AC	26%	58%	16%
EC	25%	60%	15%
VF	28%	42%	30%
Combined	27%	54%	19%
Rank	2	1	3

Table 5.62: External Characteristics with respect to Objective 1 - ranking after round 1;
$C.R. = 0,001\%$.

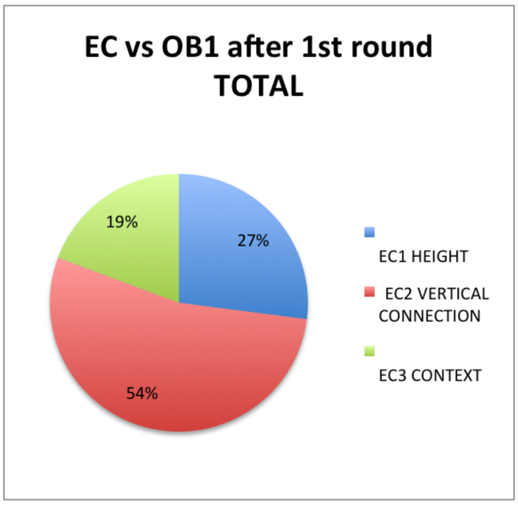


Figure 5.35: External Characteristics with respect to Objective 1: ranking average after round 1.

External Characteristics with respect to Objective 2 (Fire brigade effectiveness).
Results are shown in Table 5.63 and Figure 5.36.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
AC	29%	17%	54%
EC	29%	23%	48%
VF	25%	47%	28%
Combined	29%	28%	43%
Rank	2	3	1

Table 5.63: External Characteristics with respect to Objective 2 - ranking after round 1;
$C.R. = 0,8\%$.

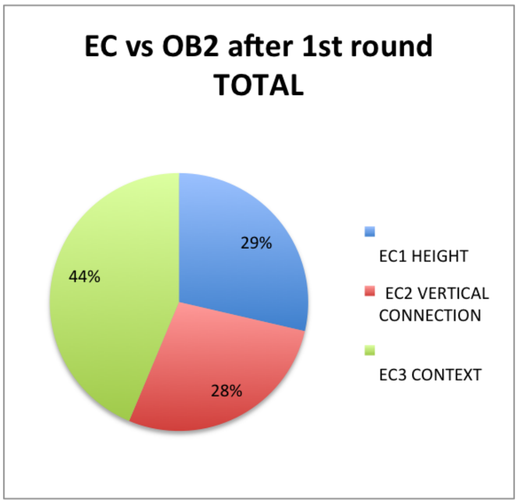


Figure 5.36: External Characteristics with respect to Objective 2: ranking average after round 1.

External Characteristics with respect to Objective 3 (Fire and smoke spread).
Results are shown in Table 5.64 and Figure 5.37.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
AC	33%	53%	14%
EC	30%	51%	19%
VF	17%	58%	25%
Combined	27%	54%	19%
Rank	2	1	3

Table 5.64: External Characteristics with respect to Objective 3 - ranking after round 1;
$C.R. = 3,2\%$.

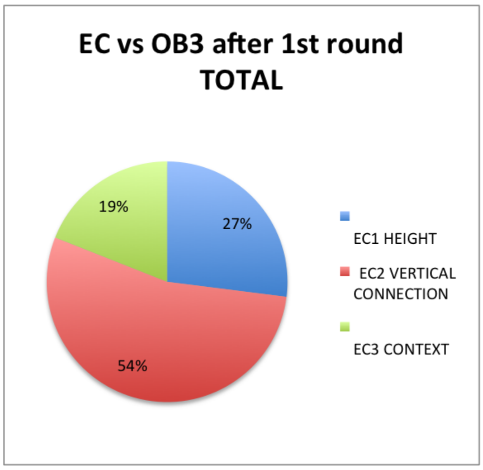


Figure 5.37: External Characteristics with respect to Objective 3: ranking average after round 1.

Internal Characteristics with respect to Objective 1 (Evacuation).
Results are shown in Table 5.65 and Figure 5.38.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
AC	33%	53%	14%
EC	29%	51%	20%
VF	18%	52%	30%
Combined	26%	53%	21%
Rank	2	1	3

Table 5.65: Internal Characteristics with respect to Objective 1 - ranking after round 1; $C.R. = 0,07\%$.

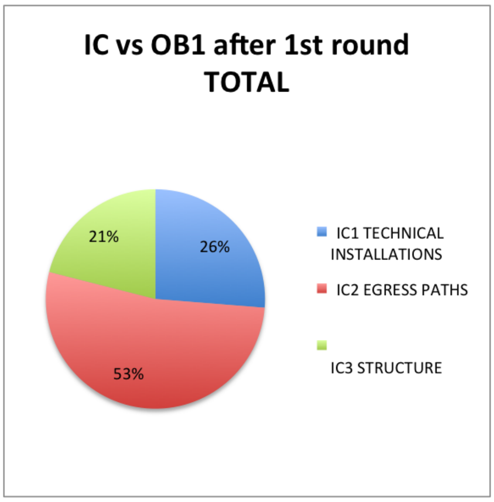


Figure 5.38: Internal Characteristics with respect to Objective 1: ranking average after round 1.

Internal Characteristics with respect to Objective 2 (Fire brigade effectiveness).
Results are shown in Table 5.66 and Figure 5.39.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
AC	41%	24%	35%
EC	41%	25%	34%
VF	30%	36%	35%
Combined	36%	23%	41%
Rank	2	3	1

Table 5.66: Internal Characteristics with respect to Objective 2 - ranking after round 1; $C.R. = 2,3\%$.

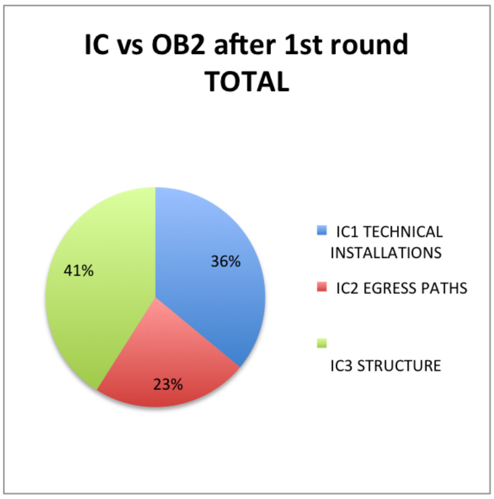


Figure 5.39: Internal Characteristics with respect to Objective 1: ranking average after round 1.

Internal Characteristics with respect to Objective 3 (Fire and smoke spread).
Results are shown in Table 5.67 and Figure 5.40.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
AC	55%	18%	27%
EC	61%	11%	28%
VF	25%	24%	51%
Combined	46%	18%	36%
Rank	1	3	2

Table 5.67: Internal Characteristics with respect to Objective 3 - ranking after round 1;
$C.R. = 0,2\%$.

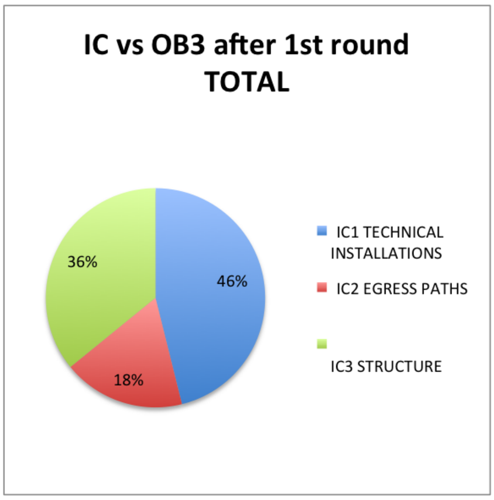


Figure 5.40: Internal Characteristics with respect to Objective 1: ranking average after round 1.

From data shown above, the necessity to perform the second round becomes evident. According to the stopping criteria that consider concordance, none of the panels has $W \geq 0,7$. The worst concordance is registered for the "Panel 3: fire brigade" in judgments given both to the External Characteristics (EC vs OB1: W=0,1; EC vs OB2: W=0,1; EC vs OB3: W=0,3) and to the Internal Characteristics (IC vs OB1: W=0,3; IC vs OB2: W=0,1; IC vs OB3: W=0,1). The other panels demonstrated an higher internal concordance $(0,3 < W < 0,7)$ however lower than the acceptable limit (W=0,7).

In the follow are shown graphs summing up the final judgments from round 1.

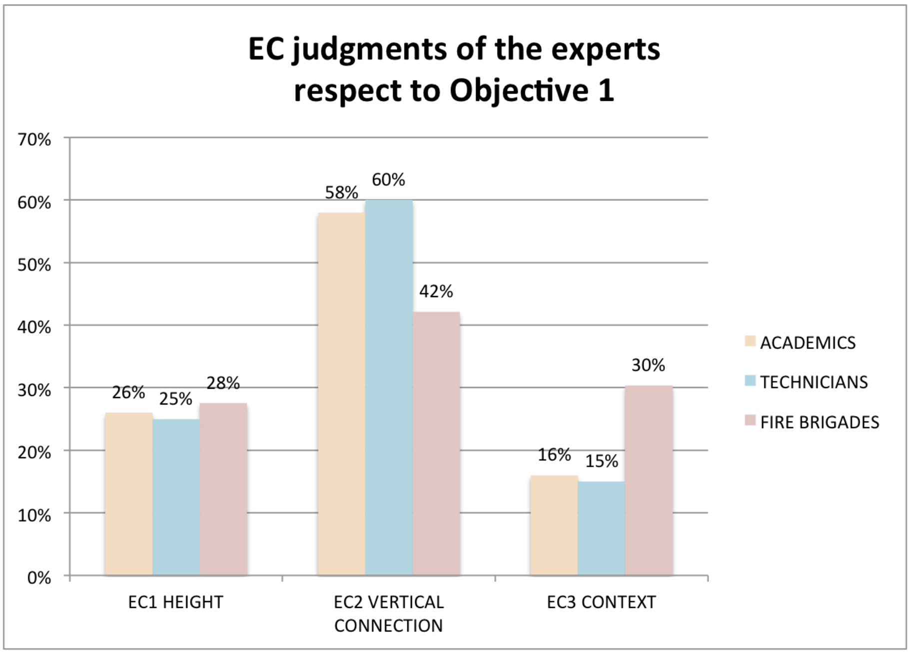


Figure 5.41: External Characteristics with respect to Objective 1: ranking from the three panels.

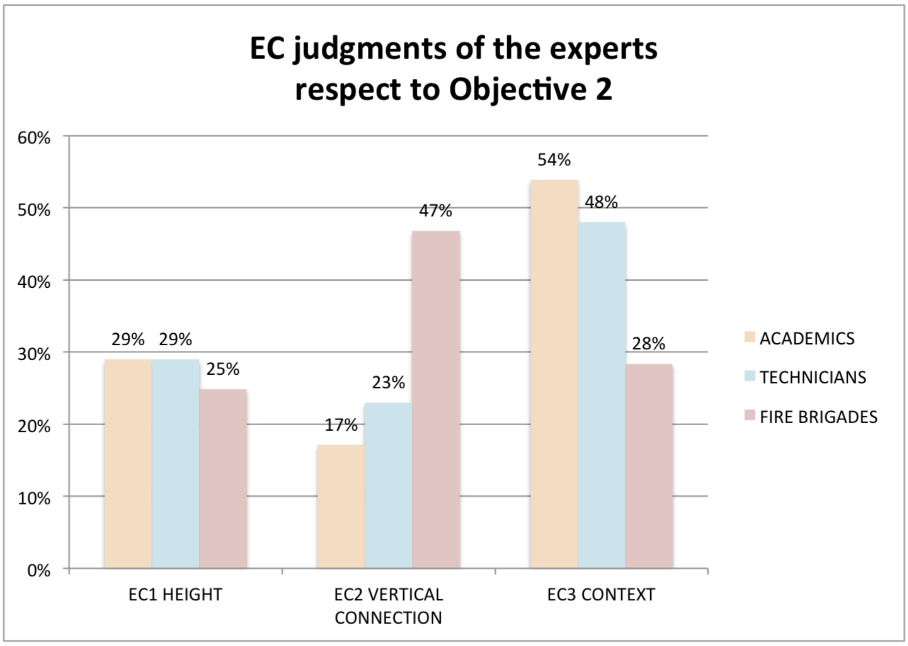


Figure 5.42: External Characteristics with respect to Objective 2: ranking from the three panels.

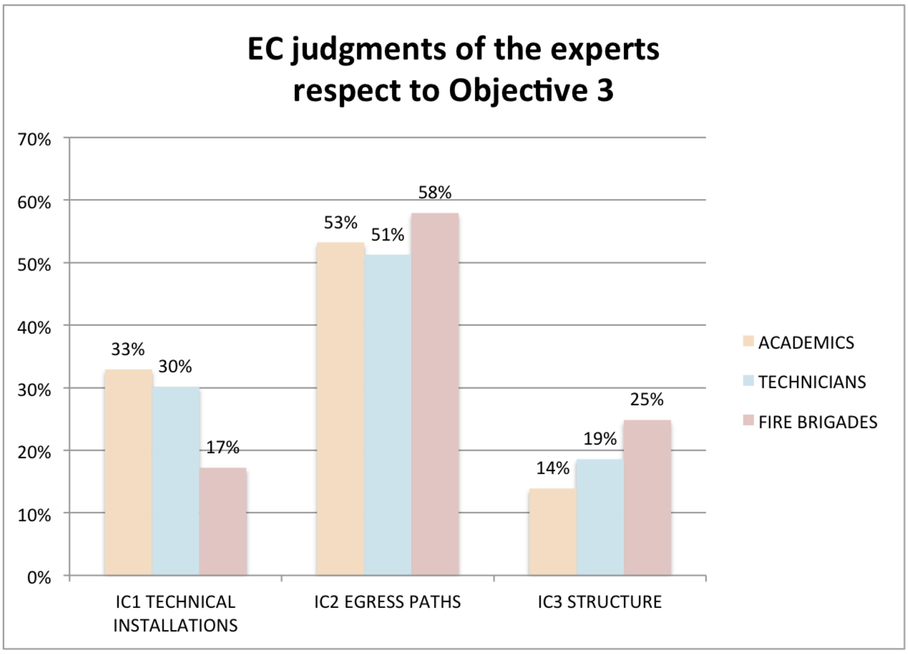


Figure 5.43: External Characteristics with respect to Objective 3: ranking from the three panels.

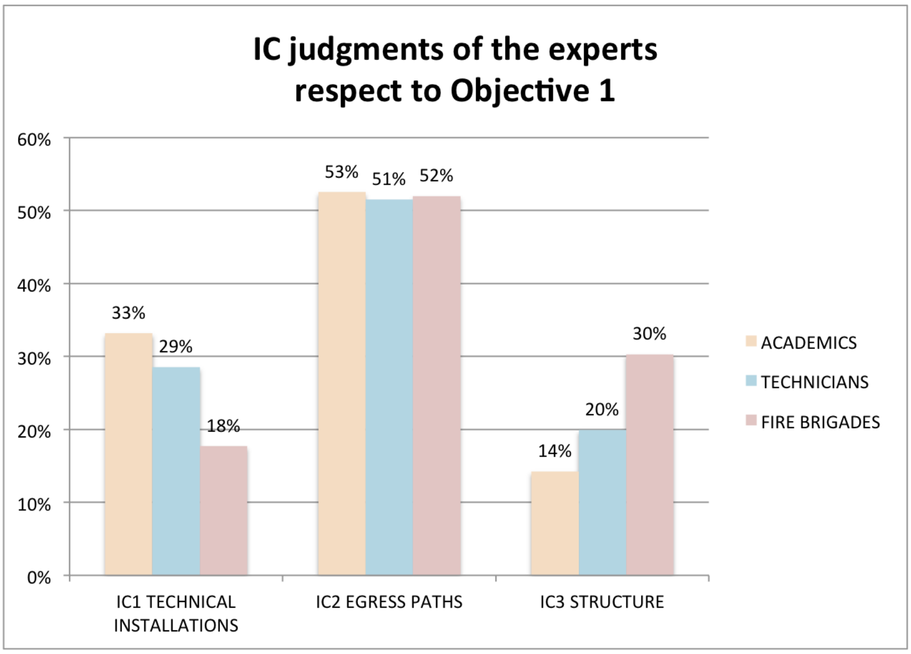


Figure 5.44: Internal Characteristics with respect to Objective 1: ranking from the three panels.

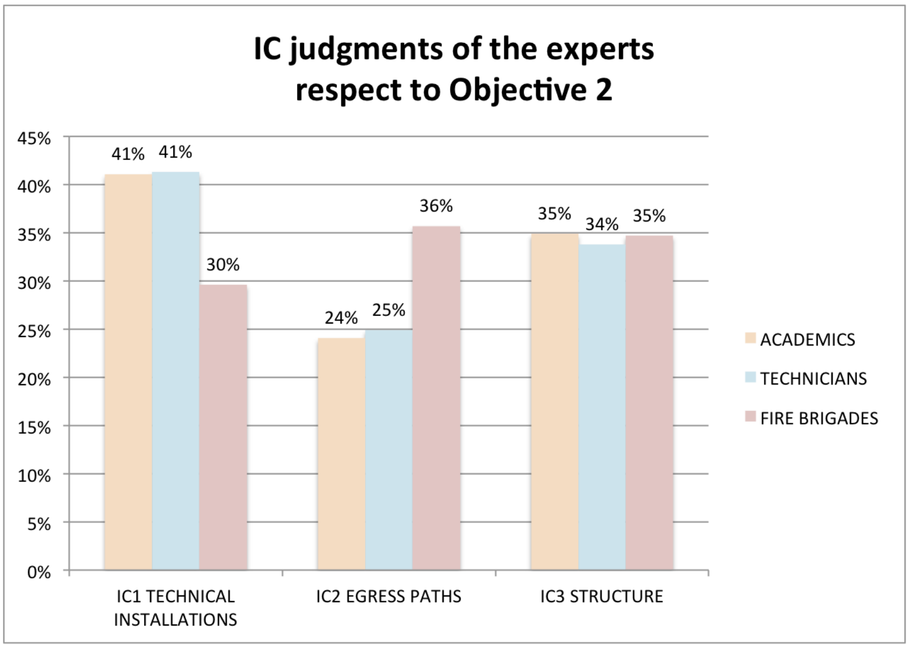


Figure 5.45: Internal Characteristics with respect to Objective 2: ranking from the three panels.

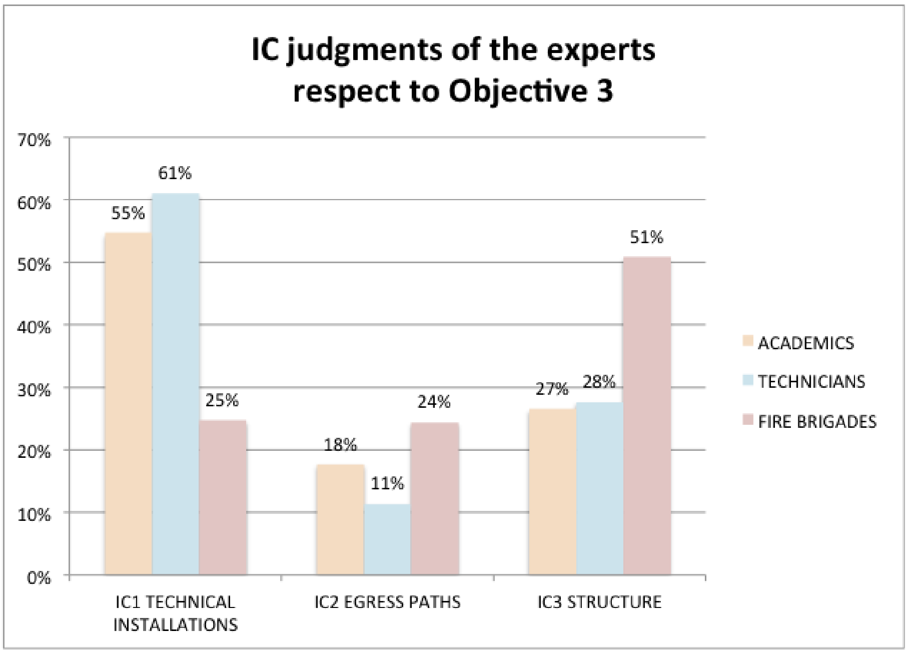


Figure 5.46: Internal Characteristics with respect to Objective 3: ranking from the three panels.

5.2.3 Delphi's second round

In this round of Delphi, a feedback is provided to the experts and the discussion among them is solicited in order to confirm the judgments given in the first round. Resuming tables and graphs referred to their panel were presented to the experts and it was asked them to think again about the judgments they gave. This time, experts had just to attribute percentages to each Characteristic with respect to each Objective, setting up a ranking both of External and Internal Characteristics with respect to each Objective. The final mean of the judgments was calculated for each panel as the arithmetic mean of the percentages with respect to each Objective. Since they aren't given, in this second round, in pairwise judgments, no Saaty's matrix has been built and no C.I. has been checked. For each panel only the two Delphi's stopping criteria were controlled (W $\geq$ 0,7 or mean rankings for two successive rounds not significantly different).

For "panel 1: Academics" and "panel 2: Technicians", in the second round the same interview methodology used in the first one was used. Feedback was shown by means of papers and judgments were collected from each one expert at a time.

Since in the "panel 3: Fire brigades" very low values of concordance were reached in the first round, in the second round a different methodology of data collection was adopted. A meeting with all the ten fire brigades experts was arranged and the feedback from the first round was presented by means of a public presentation. All the experts were then solicited to discuss together in order to motivate the answers they give in first round; with this methodology, misunderstandings in the questions from the first round were solved and levels of concordance increased sensibly. In the following sections the ranking results for each Objective and for each panel are shown; for each table W is reported.

A graph showing the mean ranking for the panel in second Delphi round is associated to each table.

5.2.3.1 Panel 1: academics

External Characteristics with respect to Objective 1 (Evacuation).
In this round academics reviewed their judgments and the two stopping criteria were both reached: $W = 0,7$ and variation in percentages were not significant. Results are shown in Table 5.68 and Figure 5.47.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
AC01	27%	60%	13%
AC02	14%	75%	11%
AC03	20%	60%	20%
AC04	70%	15%	15%
AC05	24%	68%	8%
AC06	34%	41%	25%
AC07	19%	55%	26%
AC08	40%	40%	20%
AC09	20%	71%	9%
AC10	25%	60%	15%
Combined	29%	55%	16%
Rank	2	1	3

Table 5.68: External Characteristics with respect to Objective 1 - Panel 1 - second round; $W = 0,7$.

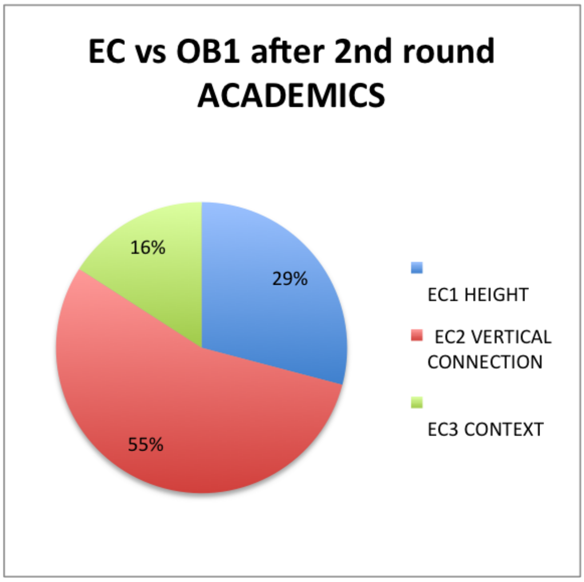


Figure 5.47: External Characteristics with respect to Objective 1: mean ranking from Panel 1 - second round.

External Characteristics with respect to Objective 2 (Fire brigade effectiveness).
In this round academics reviewed their judgments and the two stopping criteria were both reached: $W = 0,7$ and variation in percentages were not significant. Results are shown in Table 5.69 and Figure 5.48.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
AC01	30%	25%	45%
AC02	23%	12%	65%
AC03	15%	30%	55%
AC04	20%	10%	70%
AC05	24%	9%	67%
AC06	24%	13%	63%
AC07	20%	25%	55%
AC08	35%	30%	35%
AC09	20%	18%	62%
AC10	30%	25%	45%
Combined	24%	20%	56%
Rank	2	3	1

Table 5.69: External Characteristics with respect to Objective 2 - Panel 1- second round; $W = 0,7$.

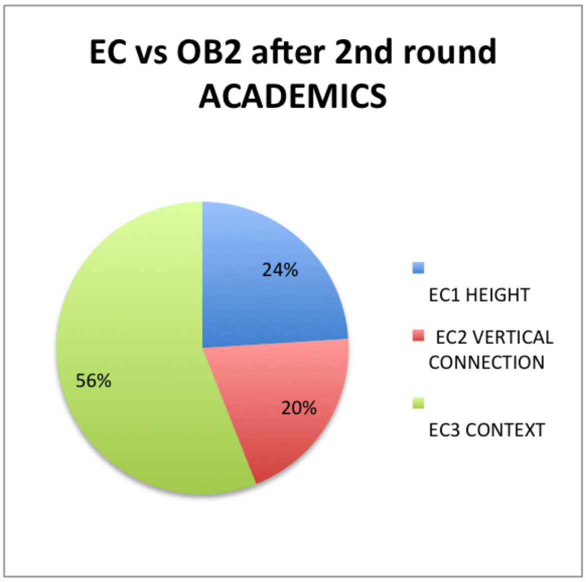


Figure 5.48: External Characteristics with respect to Objective 2: mean ranking from Panel 1 - second round.

External Characteristics with respect to Objective 3 (Fire and smoke spread).
In this round academics reviewed their judgments and the two stopping criteria were both reached: $W = 0,7$ and variation in percentages were not significant. Results are shown in Table 5.70 and Figure 5.49.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
AC01	30%	60%	10%
AC02	47%	47%	6%
AC03	40%	30%	30%
AC04	20%	70%	10%
AC05	32%	61%	7%
AC06	40%	40%	20%
AC07	15%	66%	19%
AC08	40%	50%	10%
AC09	20%	73%	7%
AC10	30%	50%	20%
Combined	31%	55%	14%
Rank	2	1	3

Table 5.70: External Characteristics with respect to Objective 3 - Panel 1- second round; $W = 0,7$.

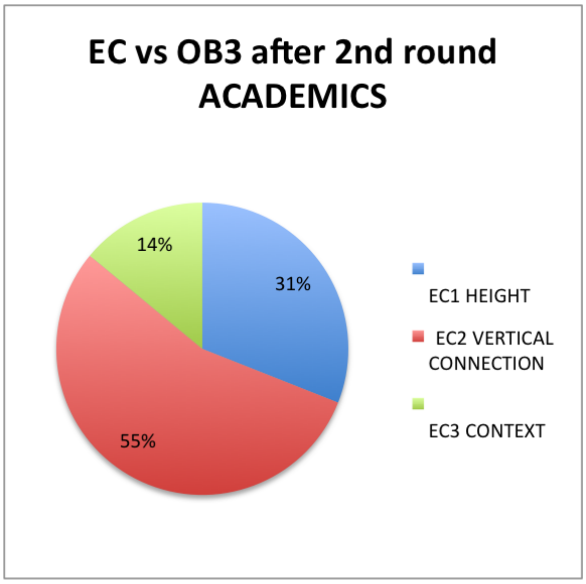


Figure 5.49: External Characteristics with respect to Objective 3: mean ranking from Panel 1 - second round.

Internal Characteristics with respect to Objective 1 (Evacuation).
In this round academics reviewed their judgments and the two stopping criteria were both reached: $W = 0,7$ and variation in percentages were not significant. Results are shown in Table 5.71 and Figure 5.50.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
AC01	35%	45%	20%
AC02	45%	47%	8%
AC03	24%	63%	13%
AC04	35%	50%	15%
AC05	11%	65%	24%
AC06	50%	29%	21%
AC07	19%	71%	10%
AC08	25%	50%	25%
AC09	42%	46%	12%
AC10	25%	60%	15%
Combined	31%	53%	16%
Rank	2	1	3

Table 5.71: Internal Characteristics with respect to Objective 1 - Panel 1- second round; $W = 0,7$.

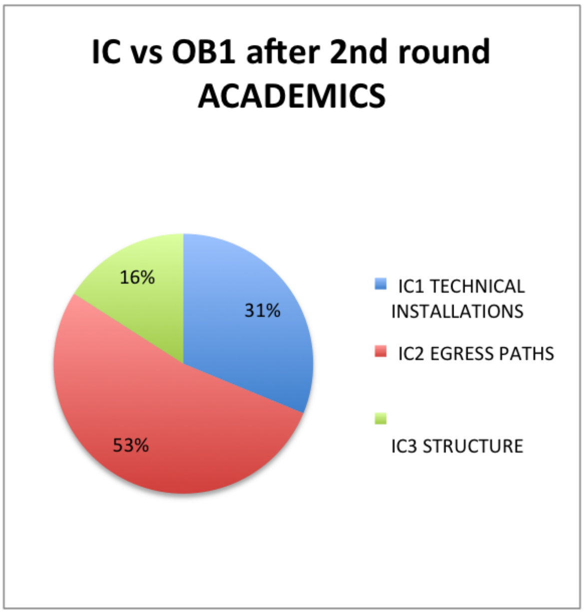


Figure 5.50: Internal Characteristics with respect to Objective 1: mean ranking from Panel 1 - second round.

Internal Characteristics with respect to Objective 2 (Fire brigade effectiveness).
In the second round, despite of the new formulation of percentages from most of the experts, W concordance didn't increased. Only the second stopping criteria was reached:

- IC1: 41% in first round, 40% in second round; variation of 1%;
- IC2: 24% in first round, 28% in second round; variation of 4%;
- IC3: 35% in first round, 32% in second round; variation of 3%;

Since there was no significant variation in percentages from first to second round, we accepted the following results as definitive. Results are shown in Table 5.72 and Figure 5.51.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
AC01	35%	30%	35%
AC02	65%	15%	20%
AC03	60%	20%	20%
AC04	30%	40%	30%
AC05	26%	29%	45%
AC06	30%	30%	40%
AC07	30%	20%	50%
AC08	45%	30%	25%
AC09	20%	50%	30%
AC10	55%	20%	25%
Combined	40%	28%	32%
Rank	1	3	2

Table 5.72: Internal Characteristics with respect to Objective 2 - Panel 1- second round; $W = 0,1$.

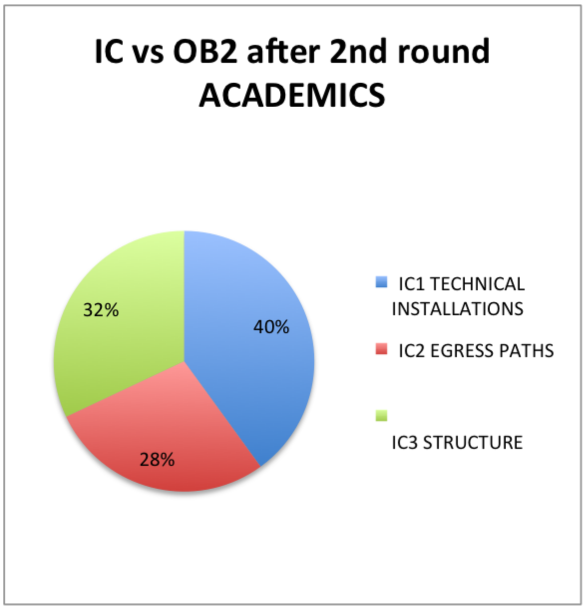


Figure 5.51: Internal Characteristics with respect to Objective 1: mean ranking from Panel 1- second round.

Internal Characteristics with respect to Objective 3 (Fire and smoke spread).
In second round was reached for these judgments an high degree of concordance: $W = 0,8$. Results are shown in Table 5.73 and Figure 5.52.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
AC01	55%	20%	25%
AC02	50%	20%	30%
AC03	60%	20%	20%
AC04	50%	20%	30%
AC05	69%	12%	19%
AC06	60%	20%	20%
AC07	57%	12%	31%
AC08	60%	30%	10%
AC09	60%	10%	30%
AC10	50%	25%	25%
Combined	57%	19%	24%
Rank	1	3	2

Table 5.73: Internal Characteristics with respect to Objective 3 - Panel 1 - second round; $W = 0,8$.

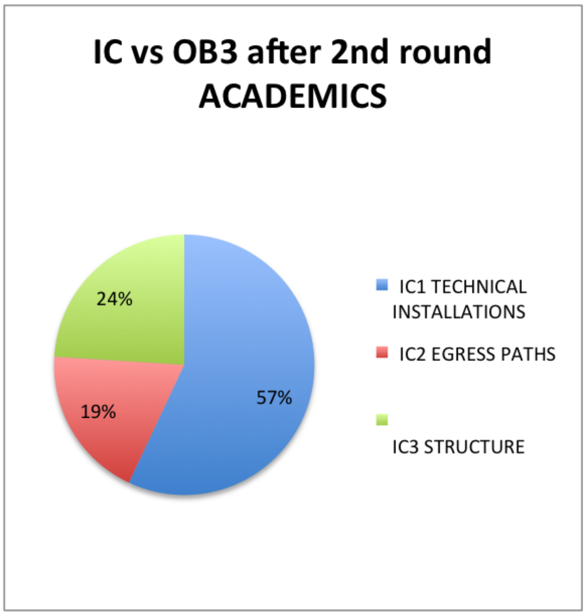


Figure 5.52: Internal Characteristics with respect to Objective 1: mean ranking from Panel 1 - second round.

5.2.3.2 Panel 2: technicians and practitioners

External Characteristics with respect to Objective 1 (Evacuation).
In this round technicians reviewed their judgments and the two stopping criteria were both reached: $W = 0,7$ and variation in percentages were not significant. Results are shown in Table 5.74 and Figure 5.53.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
EC01	27%	60%	13%
EC02	30%	50%	20%
EC03	20%	60%	20%
EC04	35%	45%	20%
EC05	20%	71%	9%
EC06	20%	65%	15%
EC07	25%	60%	15%
EC08	20%	30%	50%
EC09	16%	76%	8%
EC10	25%	55%	15%
Combined	24%	57%	19%
Rank	2	1	3

Table 5.74: External Characteristics with respect to Objective 1 - Panel 2 - second round; $W = 0,7$.

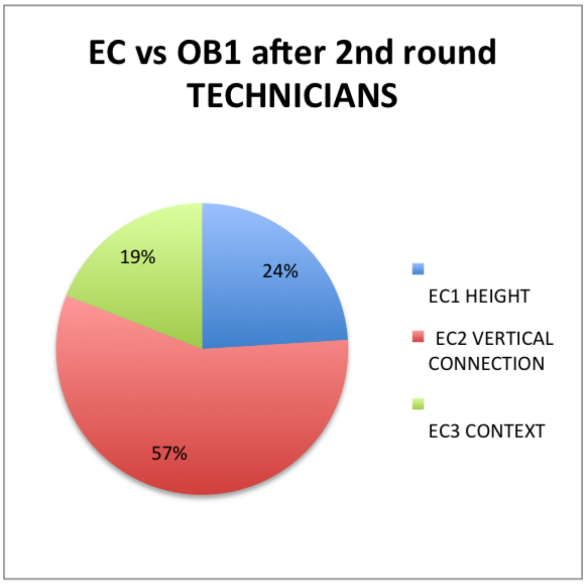


Figure 5.53: External Characteristics with respect to Objective 1: mean ranking from Panel 2 - second round.

External Characteristics with respect to Objective 2 (Fire brigade effectiveness).
In second round was reached for these judgments an high degree of concordance: $W = 0,7$. Results are shown in Table 5.75 and Figure 5.54.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
EC01	30%	25%	45%
EC02	10%	15%	75%
EC03	15%	30%	55%
EC04	30%	35%	35%
EC05	18%	20%	62%
EC06	25%	35%	40%
EC07	30%	25%	45%
EC08	20%	30%	50%
EC09	7%	61%	32%
EC10	20%	18%	62%
Combined	21%	29%	50%
Rank	2	3	1

Table 5.75: External Characteristics with respect to Objective 2 - Panel 2 - second round; $W = 0,7$.

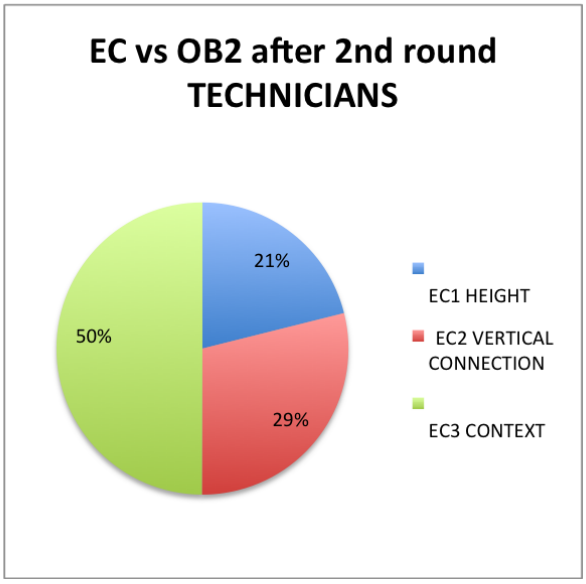


Figure 5.54: External Characteristics with respect to Objective 2: mean ranking from Panel 2 - second round.

External Characteristics with respect to Objective 3 (Fire and smoke spread).
In this round technicians reviewed their judgments and the two stopping criteria were both reached: $W = 0,7$ and variation in percentages were not significant. Results are shown in Table 5.76 and Figure 5.55.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
EC01	30%	60%	10%
EC02	40%	50%	10%
EC03	40%	35%	25%
EC04	40%	50%	10%
EC05	30%	60%	10%
EC06	63%	22%	15%
EC07	30%	50%	20%
EC08	40%	50%	10%
EC09	7%	47%	46%
EC10	30%	49%	21%
Combined	34%	48%	18%
Rank	2	1	3

Table 5.76: External Characteristics with respect to Objective 3 - Panel 2 - second round; $W = 0,7$.

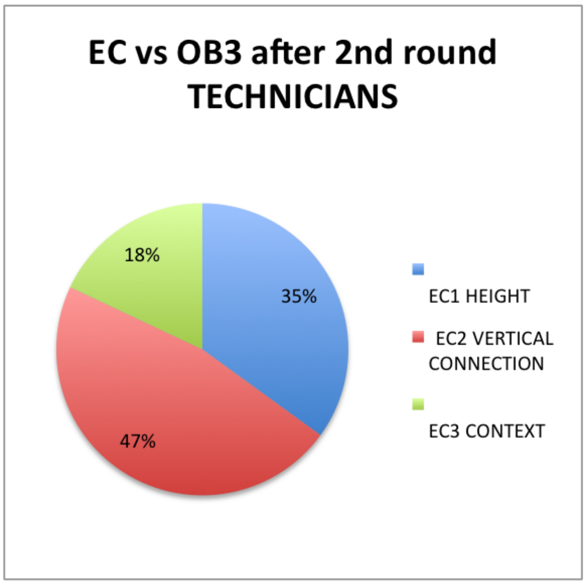


Figure 5.55: External Characteristics with respect to Objective 3: mean ranking from Panel 2 - second round.

Internal Characteristics with respect to Objective 1 (Evacuation).
In this round technicians reviewed their judgments and the two stopping criteria were both reached: $W = 0,7$ and variation in percentages were not significant. Results are shown in Table 5.77 and Figure 5.56.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
EC01	35%	45%	20%
EC02	30%	45%	25%
EC03	24%	63%	13%
EC04	25%	50%	25%
EC05	42%	46%	12%
EC06	15%	35%	40%
EC07	25%	60%	15%
EC08	30%	60%	10%
EC09	14%	74%	12%
EC10	27%	55%	18%
Combined	27%	53%	20%
Rank	2	1	3

Table 5.77: Internal Characteristics with respect to Objective 1 - Panel 2 - second round; $W = 0,7$.

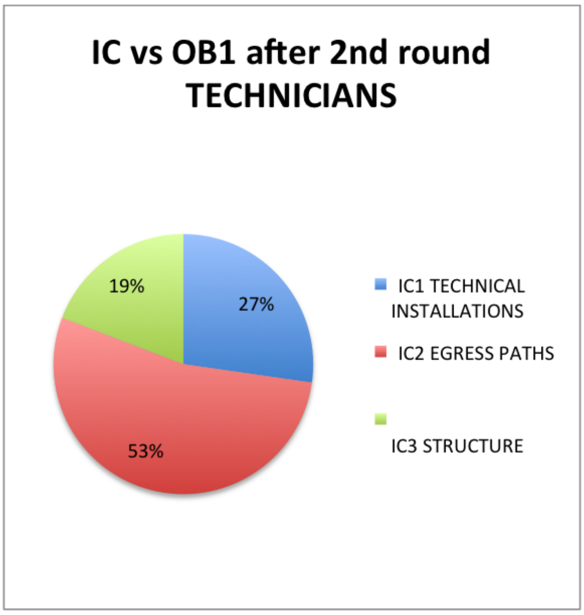


Figure 5.56: Internal Characteristics with respect to Objective 1: mean ranking from Panel 2 - second round.

Internal Characteristics with respect to Objective 2 (Fire brigade effectiveness).
In the second round there were only few changes in percentages from the experts, therefore W concordance didn't increased. Only the second stopping criteria was reached:

- IC1: 41% in first round, 41% in second round; variation of 0%;
- IC2: 25% in first round, 25% in second round; variation of 0%;
- IC3: 34% in first round, 34% in second round; variation of 0%;

Since there was no variation in percentages from first to second round, we accepted the following results as definitive. Results are shown in Table 5.54 and Figure 5.27.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
EC01	35%	30%	35%
EC02	47%	6%	47%
EC03	20%	20%	60%
EC04	40%	40%	20%
EC05	20%	50%	30%
EC06	30%	30%	40%
EC07	55%	20%	25%
EC08	50%	30%	20%
EC09	46%	9%	45%
EC10	63%	18%	19%
Combined	41%	25%	34%
Rank	1	3	2

Table 5.78: Internal Characteristics with respect to Objective 2 - Panel 2 - second round; $W = 0,2$.

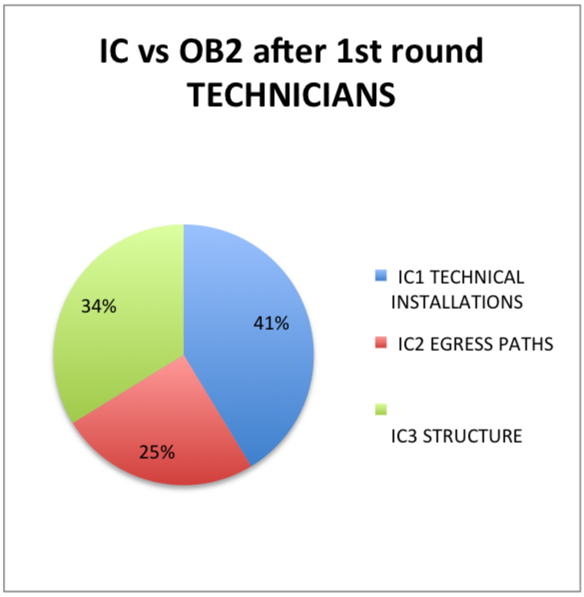


Figure 5.57: Internal Characteristics with respect to Objective 1: mean ranking from Panel 2 - second round.

Internal Characteristics with respect to Objective 3 (Fire and smoke spread).
In second round was reached for these judgments an high degree of concordance: $W = 0,8$. Results are shown in Table 5.79 and Figure 5.58.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
EC01	61%	8%	31%
EC02	68%	10%	22%
EC03	60%	20%	20%
EC04	60%	30%	10%
EC05	60%	10%	30%
EC06	71%	12%	17%
EC07	50%	25%	25%
EC08	50%	25%	25%
EC09	67%	9%	24%
EC10	50%	25%	25%
Combined	60%	17%	23%
Rank	1	3	2

Table 5.79: Internal Characteristics with respect to Objective 3 - Panel 2 - second round; $W = 0,8$.

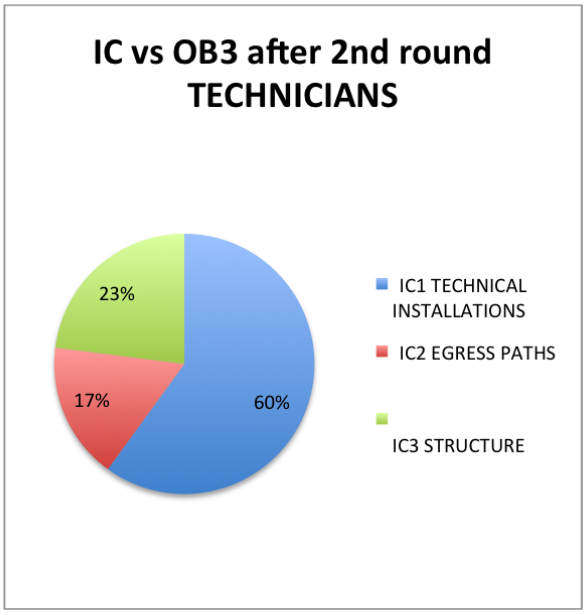


Figure 5.58: Internal Characteristics with respect to Objective 1: mean ranking from Panel 2 - second round.

5.2.3.3 Panel 3: fire brigades

External Characteristics with respect to Objective 1 (Evacuation).
In second round was reached for these judgments an high degree of concordance: $W = 0,7$. Results are shown in Table 5.80 and Figure 5.59.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
VF01	8%	82%	10%
VF02	8%	80%	12%
VF03	20%	75%	15%
VF04	20%	73%	7%
VF05	15%	55%	30%
VF06	25%	40%	35%
VF07	25%	35%	40%
VF08	30%	45%	25%
VF09	20%	45%	35%
VF10	20%	50%	30%
Combined	19%	58%	23%
Rank	3	1	2

Table 5.80: External Characteristics with respect to Objective 1 - Panel 3 - second round; $W = 0,7$.

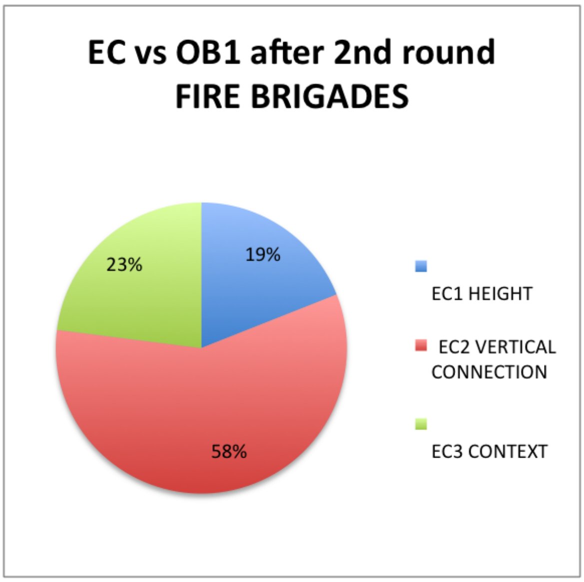


Figure 5.59: External Characteristics with respect to Objective 1: mean ranking from Panel 3 - second round.

External Characteristics with respect to Objective 2 (Fire brigade effectiveness).
In the second round there were some changes in percentages from the experts, therefore W concordance didn't increased till an acceptable level. Only the second stopping criteria was reached:

- IC1: 25% in first round, 24% in second round; variation of 1%;
- IC2: 47% in first round, 45% in second round; variation of 2%;
- IC3: 28% in first round, 32% in second round; variation of 4%;

Since there was no significant variation in percentages from first to second round, we accepted the following results as definitive.Results are shown in Table 5.81 and Figure 5.60.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
VF01	10%	80%	10%
VF02	10%	24%	66%
VF03	15%	35%	50%
VF04	18%	72%	10%
VF05	25%	45%	30%
VF06	45%	30%	25%
VF07	10%	45%	45%
VF08	20%	55%	25%
VF09	50%	20%	30%
VF10	35%	40%	25%
Combined	23%	45%	32%
Rank	3	1	2

Table 5.81: External Characteristics with respect to Objective 2 - Panel 3 - second round; $W = 0,2$.

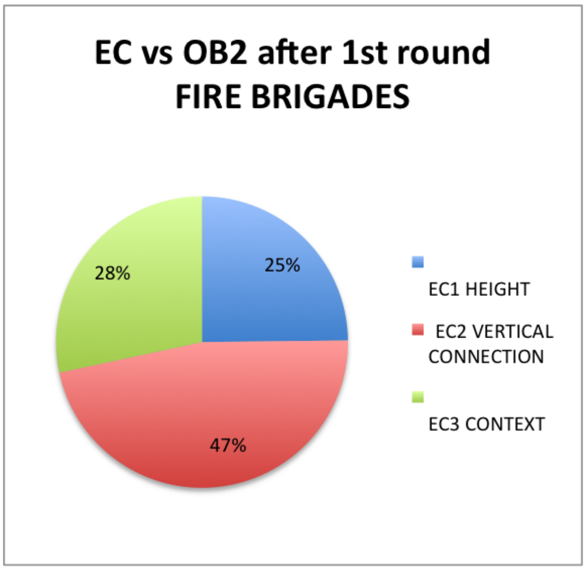


Figure 5.60: External Characteristics with respect to Objective 2: mean ranking from Panel 3 - second round.

External Characteristics with respect to Objective 3 (Fire and smoke spread).
In second round was reached for these judgments an high degree of concordance: $W = 0,8$. Results are shown in Table 5.82 and Figure 5.61.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
VF01	10%	80%	10%
VF02	10%	81%	9%
VF03	20%	60%	20%
VF04	20%	72%	8%
VF05	15%	65%	20%
VF06	30%	50%	20%
VF07	8%	60%	32%
VF08	10%	65%	25%
VF09	15%	70%	15%
VF10	15%	55%	30%
Combined	15%	66%	19%
Rank	3	1	2

Table 5.82: External Characteristics with respect to Objective 3 - Panel 3 - second round; $W = 0,8$.

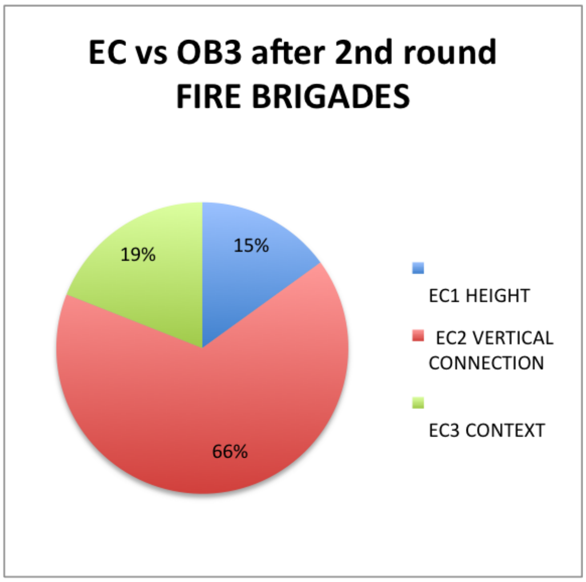


Figure 5.61: External Characteristics with respect to Objective 3: mean ranking from Panel 3 - second round.

Internal Characteristics with respect to Objective 1 (Evacuation).
In second round was reached for these judgments an high degree of concordance: $W = 0,9$. Results are shown in Table 5.83 and Figure 5.62.

Partecipant	*IC1 technical installa-tions*	*IC2 egress paths*	*IC3 structure*
VF01	10%	70%	20%
VF02	15%	70%	15%
VF03	10%	50%	40%
VF04	12%	69%	19%
VF05	22%	43%	35%
VF06	30%	40%	30%
VF07	30%	40%	30%
VF08	5%	70%	25%
VF09	11%	46%	43%
VF10	15%	60%	25%
Combined	16%	56%	28%
Rank	3	1	2

Table 5.83: Internal Characteristics with respect to Objective 1 - Panel 3 - second round; $W = 0,9$.

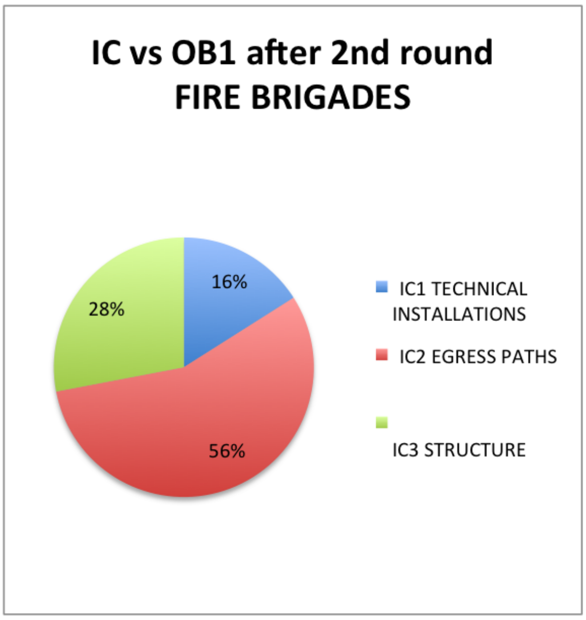


Figure 5.62: Internal Characteristics with respect to Objective 1: mean ranking from Panel 3 - second round.

Internal Characteristics with respect to Objective 2 (Fire brigade effectiveness).
This is the only case in which W decreased from first to second round; however means of judgments from second round are completely according with means in second round. Only the second stopping criteria was reached:

- IC1: 30% in first round, 31% in second round; variation of 1%;
- IC2: 36% in first round, 37% in second round; variation of 1%;
- IC3: 35% in first round, 32% in second round; variation of 3%;

Variation in percentages are not significant and the three judgments mean reflect the total lack of concordance in the panel (the three means are almost 1/3 each one). Results are shown in Table 5.84 and Figure 5.63.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
VF01	8%	72%	20%
VF02	20%	70%	10%
VF03	50%	30%	20%
VF04	20%	60%	20%
VF05	30%	20%	60%
VF06	30%	30%	40%
VF07	40%	20%	40%
VF08	70%	20%	10%
VF09	40%	20%	40%
VF10	15%	30%	55%
Combined	31%	37%	32%
Rank	3	1	2

Table 5.84: Internal Characteristics with respect to Objective 2 - Panel 3 - second round; $W = 0,0$.

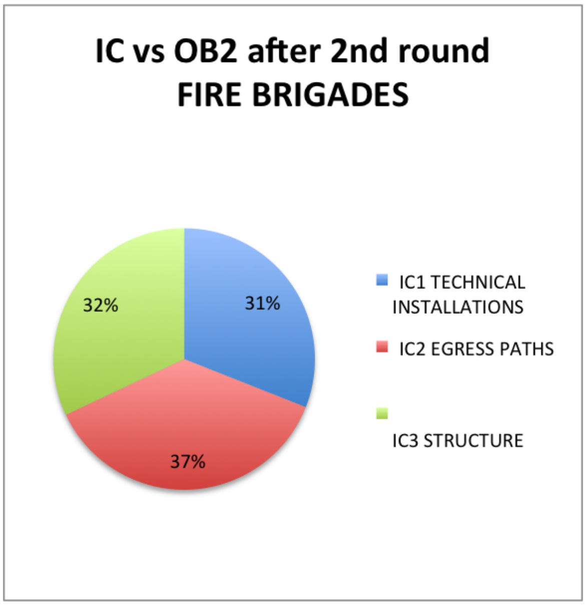


Figure 5.63: Internal Characteristics with respect to Objective 1: mean ranking from Panel 3 - second round.

Internal Characteristics with respect to Objective 3 (Fire and smoke spread).
In second round was reached for these judgments an high degree of concordance: $W = 0,8$. Results are shown in Table 5.85 and Figure 5.64.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
VF01	12%	8%	80%
VF02	30%	20%	50%
VF03	45%	20%	35%
VF04	30%	10%	60%
VF05	10%	30%	60%
VF06	50%	15%	35%
VF07	50%	5%	45%
VF08	30%	20%	50%
VF09	45%	20%	35%
VF10	30%	10%	60%
Combined	33%	16%	51%
Rank	2	3	1

Table 5.85: Internal Characteristics with respect to Objective 3 - Panel 3 - second round; $W = 0,8$.

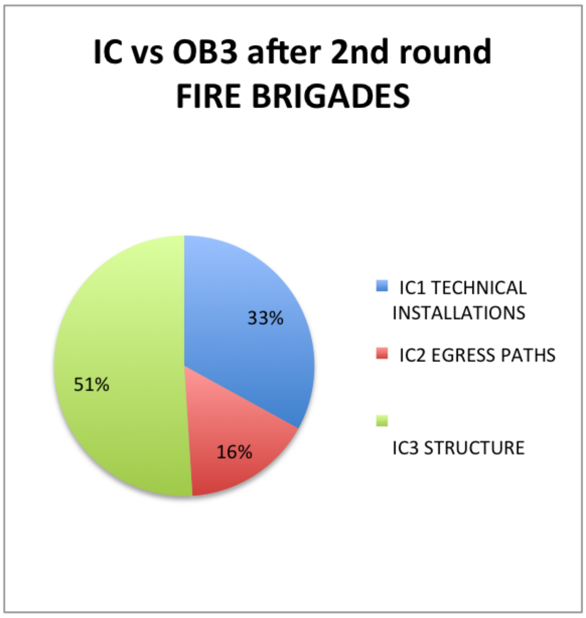


Figure 5.64: Internal Characteristics with respect to Objective 1: mean ranking from Panel 3 - second round.

5.2.3.4 Final ranking round 2

In this paragraph the mean judgments from each panel and the final mean of such values at the end of the Delphi process are shown. Concordance among the panels is not the aim of the process: it is just a request that each panel gives to reliable judgments with respect to its own experience and cultural background. The percentages reported in the following paragraphs are the weights inserted in the AHP.

External Characteristics with respect to Objective 1 (Evacuation).
Results are shown in Table 5.86 and Figure 5.65.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
AC	29%	55%	16%
EC	24%	57%	19%
VF	19%	58%	23%
Combined	24%	57%	19%
Rank	2	1	3

Table 5.86: External Characteristics with respect to Objective 1 - final ranking.

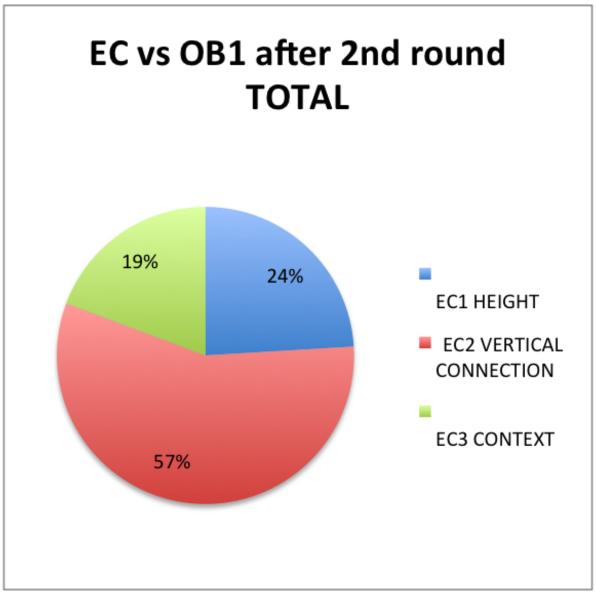


Figure 5.65: External Characteristics with respect to Objective 1: final ranking.

External Characteristics with respect to Objective 2 (Fire brigade effectiveness).
Results are shown in Table 5.87 and Figure 5.66.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
AC	24%	20%	56%
EC	21%	29%	50%
VF	24%	45%	32%
Combined	23%	31%	46%
Rank	3	2	1

Table 5.87: External Characteristics with respect to Objective 2 - final ranking.

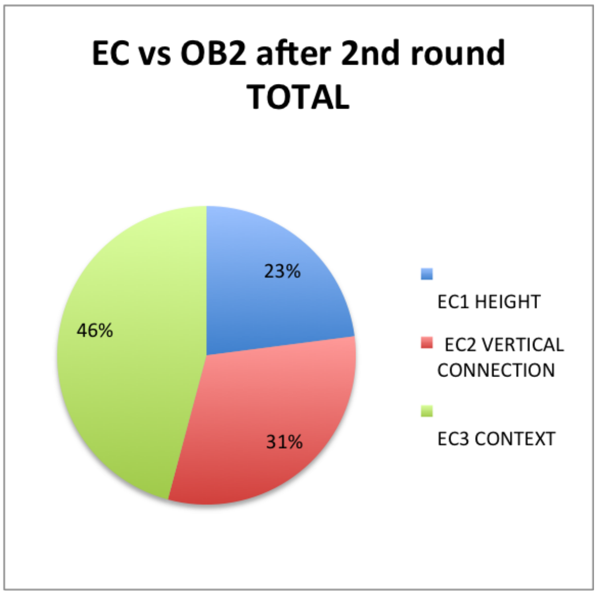


Figure 5.66: External Characteristics with respect to Objective 2: final ranking.

External Characteristics with respect to Objective 3 (Fire and smoke spread).
Results are shown in Table 5.88 and Figure 5.67.

Partecipant	*EC1 height*	*EC2 vertical connections*	*EC3 context*
AC	31%	55%	14%
EC	35%	47%	18%
VF	15%	66%	19%
Combined	27%	56%	17%
Rank	2	1	3

Table 5.88: External Characteristics with respect to Objective 3 - final ranking.

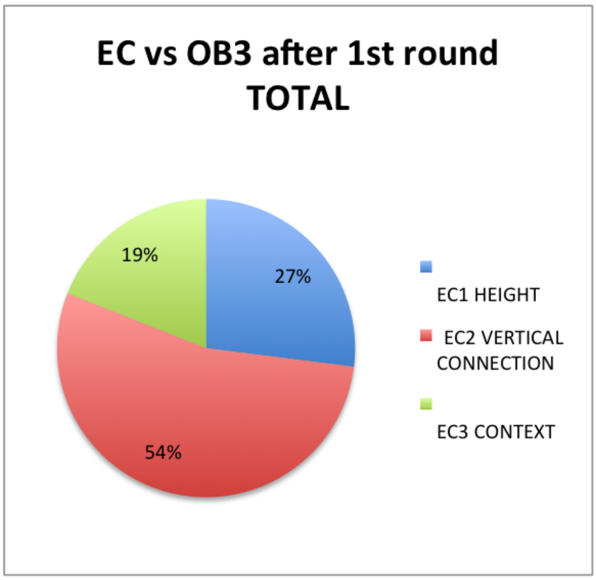


Figure 5.67: External Characteristics with respect to Objective 3: final ranking.

Internal Characteristics with respect to Objective 1 (Evacuation).
Results are shown in Table 5.89 and Figure 5.68.

Partecipant	*IC1 technical installa-tions*	*IC2 egress paths*	*IC3 structure*
AC	31%	53%	16%
EC	27%	53%	19%
VF	16%	56%	28%
Combined	25%	54%	21%
Rank	2	1	3

Table 5.89: Internal Characteristics with respect to Objective 1 - final ranking.

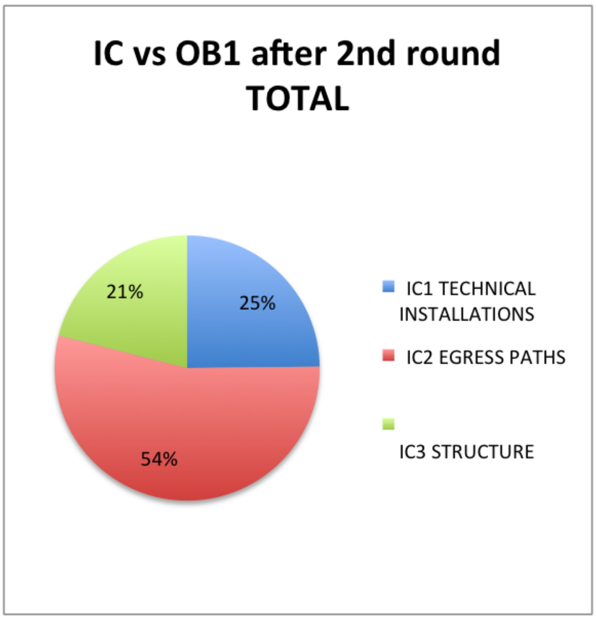


Figure 5.68: Internal Characteristics with respect to Objective 1: final ranking.

Internal Characteristics with respect to Objective 2 (Fire brigade effectiveness).
Results are shown in Table 5.90 and Figure 5.69.

Partecipant	*IC1 technical installa-tions*	*IC2 egress paths*	*IC3 structure*
AC	40%	28%	32%
EC	41%	25%	34%
VF	31%	37%	32%
Combined	37%	30%	33%
Rank	1	3	2

Table 5.90: Internal Characteristics with respect to Objective 2 - final ranking.

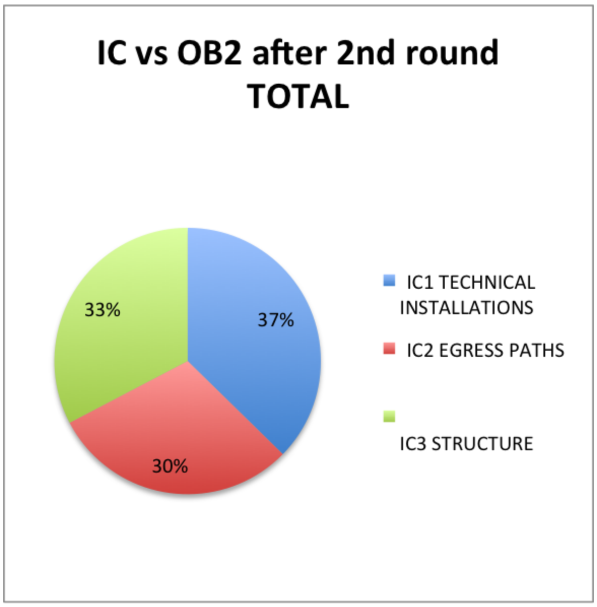


Figure 5.69: Internal Characteristics with respect to Objective 1: final ranking.

Internal Characteristics with respect to Objective 3 (Fire and smoke spread).
Results are shown in Table 5.91 and Figure 5.70.

Partecipant	*IC1 technical installations*	*IC2 egress paths*	*IC3 structure*
AC	57%	19%	24%
EC	60%	17%	23%
VF	33%	16%	51%
Combined	50%	17%	33%
Rank	1	3	2

Table 5.91: Internal Characteristics with respect to Objective 3 - final ranking.

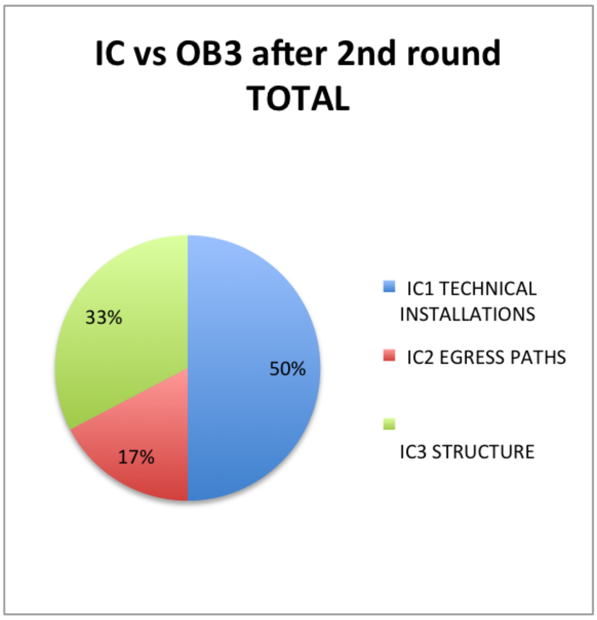


Figure 5.70: Internal Characteristics with respect to Objective 1: final ranking.

5.2.4 Sensitivity analysis

Sensitivity analysis is the study of how the variation in the output of a model can be attributed to different variations in the inputs of the model. Sensitivity analysis has been conducted for:

- each set of Factor with respect to the corresponding Characteristic and each Objective (sensitivity analysis of level 4 with respect to level 3 of the hierarchical structure);
- each set of Characteristics with respect to each Objective (sensitivity analysis of level 3 with respect to level 2 of the hierarchical structure).

Analysis has been performed by means of spreadsheets, tables and diagrams created by a Microsoft Excel plug-in.

5.2.4.1 Theoretical outline

Sensitivity analysis is useful to understand how the output depends on specified ranges for each of the input variables. Range of variation for each parameter has been found out with the worst case, likely case, and best case for that parameter.

Tornado Diagrams and Spider Charts were plotted for each Factor with respect to the Characteristics and for each Characteristic with respect to the Objectives.

Tornado Diagram
For each input variable, all other input values at their "Base case" values are set, it copies the "One Extreme" input value to the input variable cell, recalculated the worksheet, and copies the value of the output variable cell to the table. The same steps were repeated using each "Other Extreme" input value. For each input variable, the software computes the range of the output variable values (the swing), sorts the table from the largest swing down to the smallest swing, and prepares a bar chart.

Two Factors Tornado Diagram
Two-factor tornado chart are also produced, where each pair of input variables is considered. If N is the number of input variables, there are $N \cdot (N-1)/2$ pairs to evaluate. For each pair, the software considers all nine combinations of the "One Extreme", "Base Case", and "Other Extreme" input values for the two variables. For the calculation of output of each combination, the other input variables are kept at their "Base Case" values. For each pair, the software summarizes the calculations by showing the combinations of input values that produce the lowest and highest output value. Finally, the pairs are sorted by swing, and a tornado chart is created.

Spider Chart
In addition to the tornado chart, spider charts were also created to show how your model's output depends on the percentage changes for each of the model's input variables. Software's Spider uses the same base case and extreme input values as the sensitivity analysis for the tornado chart. The results are shown with each input value expressed as a percentage of the base case input value. If the base case value for an input variable is zero, that variable is not included in the Spider analysis (because it would not be possible to express an extreme or intermediate input value as a percentage of the zero base case value). The chart is an XY chart where the horizontal axis is each input value as a percentage of the base case input value and the vertical axis is the associated model output value.

5.2.4.2 Results

Sensitivity analysis of level 4 with respect to level 3
It is important to remember that weights for Factors with respect to the Characteristics are fixed by the method developer; risk indexes, that each factor can assume, are also fixed (refer to subsection 5.1.6). Sensitivity analysis for the Factors with respect to the Characteristics has been performed to understand if suggestions coming from the discussion about important Factors had in the Delphi's first round, were to be considered in the structure. Such sensitivity analysis was useful to reduce the number of parameters in the original hierarchy structure to define the definitive structure shown in Figure 5.5. Original hierarchic structure was composed by 18 Factors instead that 15 in the definitive version. In the follow, results from the sensitivity analysis performed on a hierarchic structure are shown. In that structure, in addition to the Factors considered in subsection 5.1.6, three more factors were considered:

- EF2.2 Elevators (considered in EC2 *Vertical connections*);
- EF3.2 Presence of external hydrants (considered in EC3 *Context*);
- IF1.5 Electricity power system (considered in IC1 *Technical installations*).

In each one of the following paragraphs three tables (one for each Objective) containing Factors composing the Characteristic and their percentage coming from the sensitivity analysis are reported. For each Characteristic there is a graph showing the importance of Factors for each one of the Objectives. Full results from sensitivity analysis in Appendix B.

Sensitivity analysis of External Characteristic 1: *Height*
EC1 was composed by *EF1.1: Number of Levels* and *EF1.2: Medium Height.*

	OB1 Evacuation		*OB2 Fire brigade effectiveness*		*OB3 Fire and smoke spread*	
	Input Variable	Percentage	Input Variable	Percentage	Input Variable	Percentage
EC1	EF1.1	78,5%	EF1.1	89,9%	EF1.2	90,8%
	EF1.2	21,5%	EF1.2	10,1%	EF1.1	9,2%

Table 5.92: Percentages of EF1.1 and EF1.2 from sensitivity analysis with respect to the Objectives.

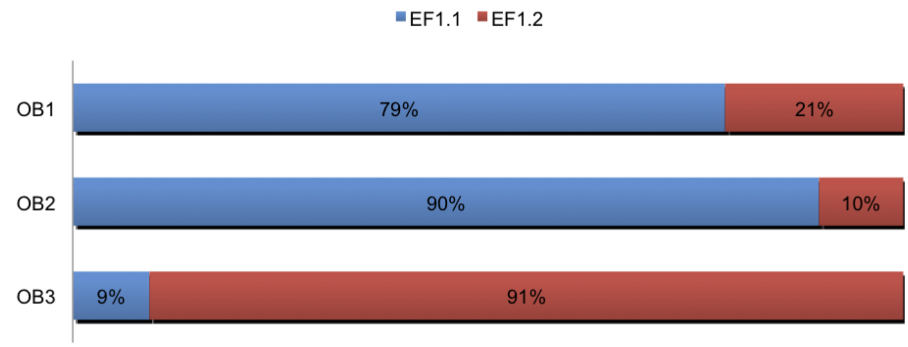


Figure 5.71: Sensitivity analysis of External Factors EF1.1 and EF 1.2 with respect to External Characteristic 1 for the three Objectives.

Both the two Factors have strong percentage on the Characteristic: none of them have been neglected after this sensitivity analysis.

Sensitivity analysis of External Characteristic 2: *Vertical connections*
EC2 was composed by *EF2.1: Stairs*, *EF2.2: Elevators* and *EF2.3: Double Heights.*

From Figure 5.72 and table 5.93 it is quite evident how Factor *EF2.2: Elevators* have no influence on the Characteristic. *EF2.2* percentage is always lower than 2%; for this reason this Factor has been neglected in the the definitive hierarchic structure.

	OB1 *Evacuation*		*OB2* *Fire brigade effectiveness*		*OB3* *Fire and smoke spread*	
	Input Variable	Percentage	Input Variable	Percentage	Input Variable	Percentage
EC2	EF2.1	97,8%	EF2.1	74,5%	EF2.3	95,4%
	EF2.3	1,5%	EF2.3	25,1%	EF2.1	2,9%
	EF2.2	0,7%	EF2.2	0,4%	EF2.2	1,6%

Table 5.93: Percentages of EF2.1 EF2.2 and EF2.3 from sensitivity analysis with respect to the Objectives.

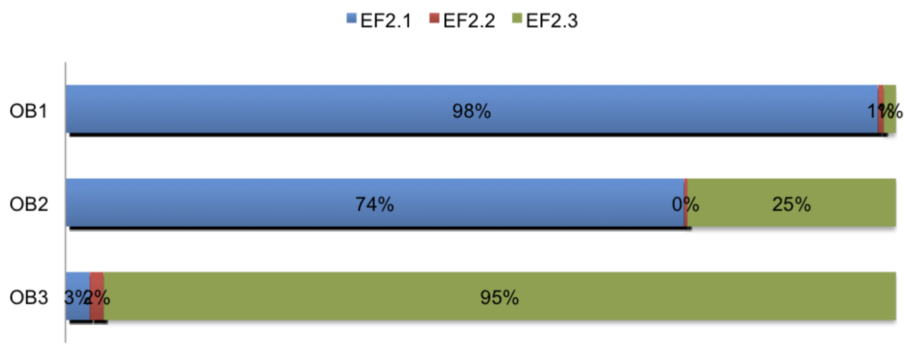


Figure 5.72: Sensitivity analysis of External Factors EF2.1, EF 2.2 and EF 2.3 with respect to External Characteristic 2 for the three Objectives.

Sensitivity analysis of External Characteristic 3: *Context*

EC3 was composed by *EF3.1: Fire Brigade response time*, *EF3.2: Presence of external hydrants* and *EF3.3: Surroundings*.

	OB1 *Evacuation*		*OB2* *Fire brigade effectiveness*		*OB3* *Fire and smoke spread*	
	Input Variable	Percentage	Input Variable	Percentage	Input Variable	Percentage
EC3	EF3.1	57,7%	EF3.1	55,2%	EF3.3	47,0%
	EF3.3	39,5%	EF3.3	43,2%	EF3.1	44,8%
	EF3.2	2,8%	EF3.2	1,6%	EF3.2	8,3%

Table 5.94: Percentages of EF3.1 EF3.2 and EF3.3 from sensitivity analysis with respect to the Objectives.

In Figure 5.73 and table 5.94 we can see that Factor *EF3.2: Presence of external hydrants* have percentage always lower than 10%; for this reason this Factor has been neglected in the the definitive hierarchic structure. Such choice coincides with the opinion collected from the experts in Delphi's first round: limiting the damages by means of hydrants can represent a severe problem for the Valuable Contents. Lots of damages to contents are due not only to the fire but also to the use of water as an extinguisher.

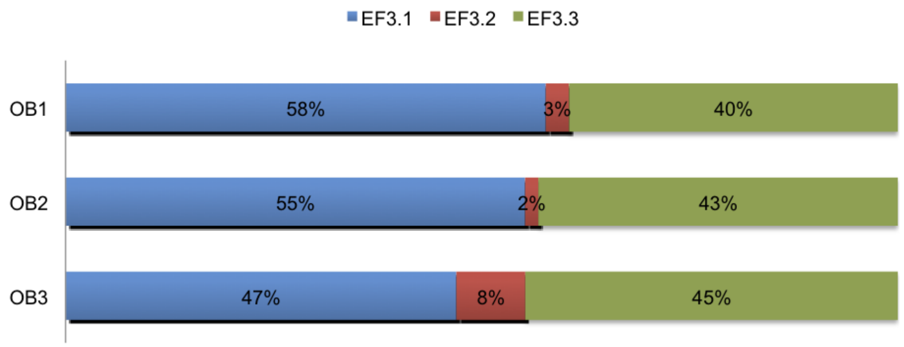


Figure 5.73: Sensitivity analysis of External Factors EF3.1, EF 3.2 and EF 3.3 with respect to External Characteristic 3 for the three Objectives.

Sensitivity analysis of Internal Characteristic 1: *Technical installations*

IC1 was composed by *IF1.1: Smoke control system*; *IF1.2: Detection system*; *IF1.3: Suppression system*; *IF1.4: Alarm system* and *IF1.5: Electricity power system*.

	OB1 *Evacuation*		*OB2* *Fire brigade effectiveness*		*OB3* *Fire and smoke spread*	
	Input Variable	Percentage	Input Variable	Percentage	Input Variable	Percentage
IC1	IF1.2	38,7%	IF1.2	33,4%	IF1.3	44,3%
	IF1.4	35,1%	IF1.4	27,3%	IF1.1	29,8%
	IF1.1	11,1%	IF1.3	23,0%	IF1.2	18,2%
	IF1.3	10,6%	IF1.1	15,5%	IF1.4	5,3%
	IF1.5	4,6%	IF1.5	0,8%	IF1.5	2,4%

Table 5.95: Percentages of IF1.1, IF1.2, IF1.3, IF1.4 and EF1.5 from sensitivity analysis with respect to the Objectives.

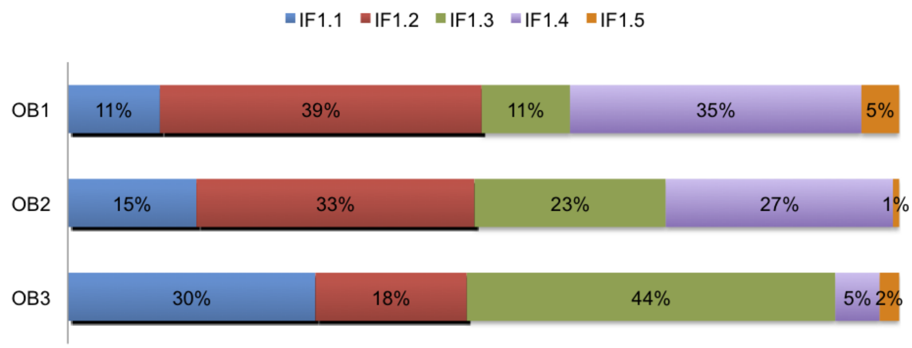


Figure 5.74: Sensitivity analysis of Internal Factors IF1.1, IF1.2, IF1.3, IF1.4 and EF1.5 with respect to External Characteristic 1 for the three Objectives.

In Figure 5.74 and table 5.95 we can see that Factor *IF1.5: Electricity power system* has percentage always lower than 5%; for this reason this Factor has been neglected in the the definitive hierarchic structure. Such choice coincides with the opinion collected from the experts in Delphi's first round: in event of fire electricity is always absent and the other technical installations have to be provided with alternative power supply.

Sensitivity analysis of Internal Characteristic 2: *Egress paths*

IC2 was composed by *IF2.1: Type of Evacuation Route*; *IF2.2: Dimension and Layout* and *IF2.3: Linings and Floorings.*

	OB1 *Evacuation*		*OB2* *Fire brigade effectiveness*		*OB3* *Fire and smoke spread*	
	Input Variable	Percentage	Input Variable	Percentage	Input Variable	Percentage
IC2	IF2.1	75,9%	IF2.1	71,5%	IF2.2	48,5%
	IF2.2	19,8%	IF2.2	20,3%	IF2.3	37,1%
	IF2.3	4,3%	IF2.3	8,2%	IF2.1	14,3%

Table 5.96: Percentages of IF2.1, IF2.2 and EF2.3 from sensitivity analysis with respect to the Objectives.

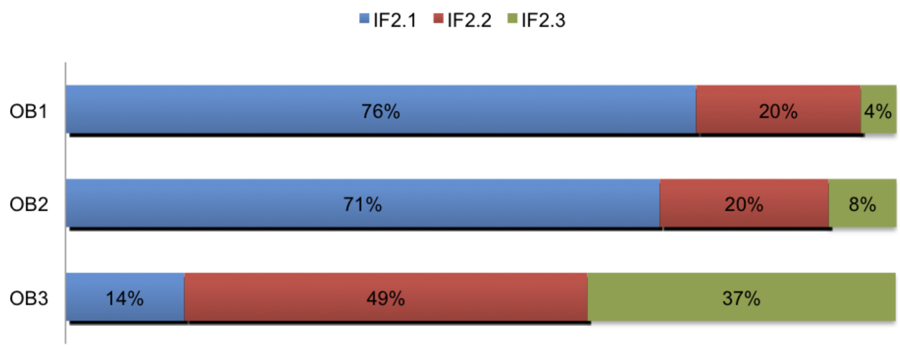


Figure 5.75: Sensitivity analysis of Internal Factors IF2.1, IF2.2 and EF2.3 with respect to External Characteristic 2 for the three Objectives.

All the three Factors have strong percentages with respect to the Characteristics: none of them has been neglected after this sensitivity analysis.

Sensitivity analysis of Internal Characteristic 3: *Structure*

IC3 was composed by *IF3.1: Vertical Structure* and *IF3.2: Horizontal Structure*.

	OB1 *Evacuation*		*OB2* *Fire brigade effectiveness*		*OB3* *Fire and smoke spread*	
	Input Variable	Percentage	Input Variable	Percentage	Input Variable	Percentage
IC3	IF3.2	59,0%	IF3.2	77,7%	IF3.2	91,1%
	IF3.1	41,0%	IF3.1	22,3%	IF3.1	8,9%

Table 5.97: Percentages of IF3.1 and EF3.2 from sensitivity analysis with respect to the Objectives.

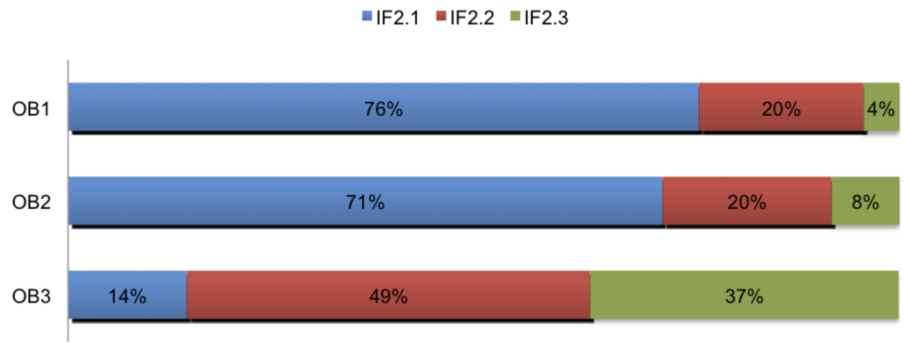


Figure 5.76: Sensitivity analysis of Internal Factors IF3.1 and EF3.2 with respect to External Characteristic 3 for the three Objectives.

The two Factors have strong percentage on the Characteristic: none of them has been neglected after this sensitivity analysis.

After the full sensitivity analysis on the hierarchic structure, three Factors have been neglected. Sensitivity analysis was performed another time for *EC2: Vertical connections*, *EC3: Context* and *IC1: Technical installations* after the cut off of the three Factors: *EF2.2 Elevators*, *EF3.2 Presence of external hydrants* and *IF1.5 Electricity power system*. In the following paragraphs the results from the sensitivity analysis on the definitive Factors are reported.

Sensitivity analysis in the definitive hierarchic structure - External Characteristic 2: *Vertical connections*

EC2 is composed, in the definitive hierarchic structure, by only two Factors: *EF2.1: Stairs* and *EF2.2: Double Heights*.

	OB1 *Evacuation*		*OB2* *Fire brigade effectiveness*		*OB3* *Fire and smoke spread*	
	Input Variable	Percentage	Input Variable	Percentage	Input Variable	Percentage
EC2	EF2.1	96,2%	EF2.1	73,2%	EF2.2	95,3%
	EF2.2	3,8%	EF2.2	26,8%	EF2.1	4,7%

Table 5.98: Percentages of EF2.1 EF2.2 from sensitivity analysis for definitive hierarchic structure with respect to the Objectives.

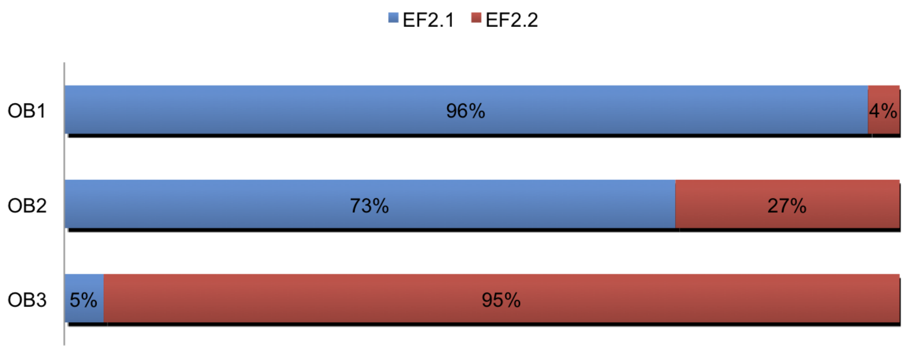


Figure 5.77: Sensitivity analysis in definitive hierarchic structure of External Factors EF2.1 and EF 2.2 with respect to External Characteristic 2 for the three Objectives.

Sensitivity analysis in the definitive hierarchic structure - External Characteristic 3: *Context*

EC3 is composed, in the definitive hierarchic structure, by only two Factors: *EF3.1: Fire Brigade response time* and *EF3.2: Surroundings*.

	OB1 *Evacuation*		*OB2* *Fire brigade effectiveness*		*OB3* *Fire and smoke spread*	
	Input Variable	Percentage	Input Variable	Percentage	Input Variable	Percentage
EC3	EF3.1	54,9%	EF3.1	54,9%	EF3.2	55,7%
	EF3.2	45,1%	EF3.2	45,1%	EF3.1	44,3%

Table 5.99: Percentages of EF3.1 and EF3.2 from sensitivity analysis for definitive hierarchic structure with respect to the Objectives.

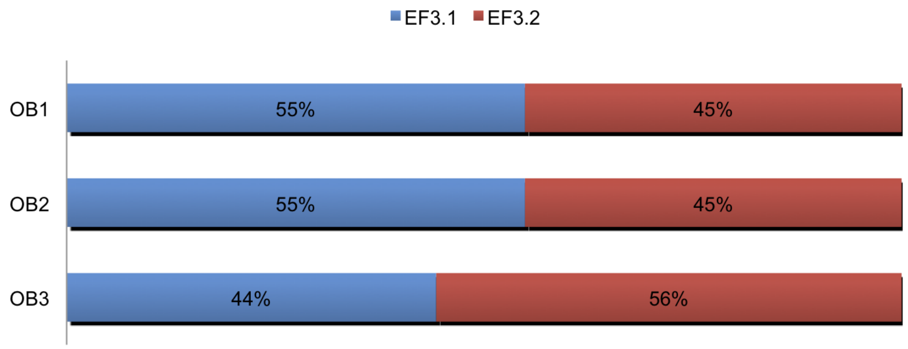


Figure 5.78: Sensitivity analysis in definitive hierarchic structure of External Factors EF3.1 and EF 3.2 with respect to External Characteristic 3 for the three Objectives.

Sensitivity analysis in the definitive hierarchic structure - Internal Characteristic 1: *Technical installations*

IC1 is composed, in the definitive hierarchic structure, by only four Factors by *IF1.1: Smoke control system*; *IF1.2: Detection system*; *IF1.3: Suppression system* and *IF1.4: Alarm system.*

	OB1 Evacuation		*OB2 Fire brigade effectiveness*		*OB3 Fire and smoke spread*	
	Input Variable	Percentage	Input Variable	Percentage	Input Variable	Percentage
IC1	IF1.2	39,3%	IF1.2	34,1%	IF1.3	44,2%
	IF1.4	36,8%	IF1.4	27,9%	IF1.1	31,3%
	IF1.1	13,3%	IF1.3	22,3%	IF1.2	17,9%
	IF1.3	10,6%	IF1.1	15,8%	IF1.4	6,5%

Table 5.100: Percentages of IF1.1, IF1.2, IF1.3 and EF1.4 from sensitivity analysis for definitive hierarchic structure with respect to the Objectives.

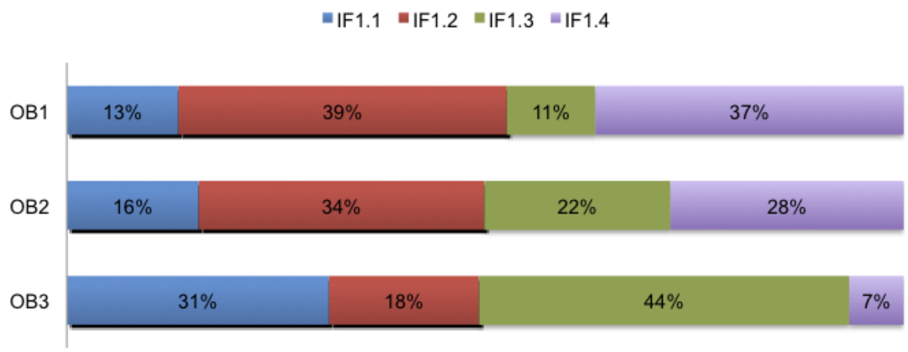


Figure 5.79: Sensitivity analysis in definitive hierarchic structure of Internal Factors IF1.1, IF1.2, IF1.3 and EF1.4 with respect to External Characteristic 1 for the three Objectives.

Sensitivity analysis of level 5 with respect to level 4

In this phase a sensitivity analysis was performed in order to check the influence of the Characteristics with respect to the Objectives. To perform this sensitivity analysis, results about risk indexes (range of variation of each Characteristic) coming from the sensitivity between level 4 and 3 and the weights coming from Delphi's second round were used.

In the following paragraphs tables and graphs (both for External Characteristics and for Internal Characteristics) containing percentages of each Characteristic with respect to the Objectives are reported.

Full results from sensitivity analysis in Appendix B.

Sensitivity analysis of External Characteristic with respect to Objectives

OB1 *Evacuation*		*OB2* *Fire brigade effectiveness*		*OB3* *Fire and smoke spread*	
Input Variable	Percentage	Input Variable	Percentage	Input Variable	Percentage
EC2	81,4%	EC1	40,5%	EC2	76,0%
EC1	16,0%	EC3	31,5%	EC1	22,4%
EC3	2,6%	EC2	28,1%	EC3	1,5%

Table 5.101: Percentages of EC1, EC2 and EC3 from sensitivity analysis with respect to the Objectives.

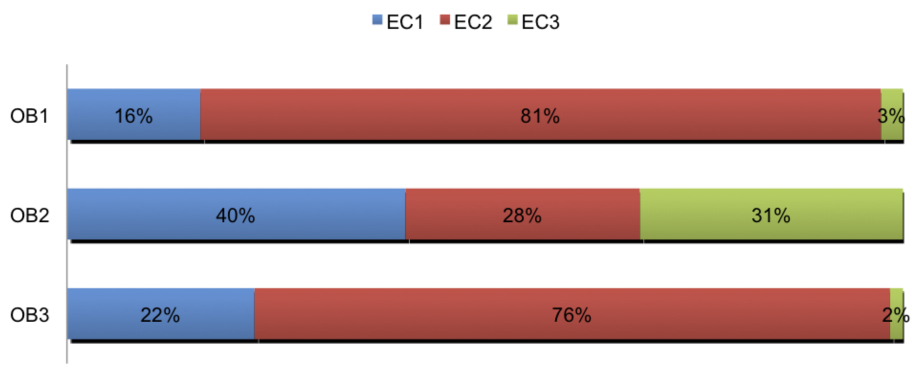


Figure 5.80: Sensitivity analysis of EC1, EC2 and EC3 with respect to the three Objectives.

Sensitivity analysis of Internal Characteristic with respect to Objectives

OB1 *Evacuation*		*OB2* *Fire brigade effectiveness*		*OB3* *Fire and smoke spread*	
Input Variable	Percentage	Input Variable	Percentage	Input Variable	Percentage
IC2	81,6%	IC3	41,2%	IC1	53,8%
IC3	10,8%	IC2	34,0%	IC3	38,0%
IC1	7,6%	IC1	24,8%	IC2	8,2%

Table 5.102: Percentages of IC1, IC2 and IC3 from sensitivity analysis with respect to the Objectives.

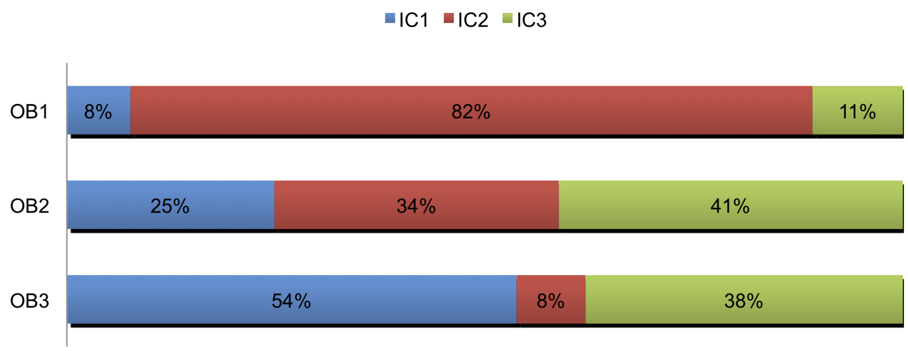


Figure 5.81: Sensitivity analysis of IC1, IC2 and IC3 with respect to the three Objectives.

Chapter 6

Risk Treatment Method

Risk treatment is the phase of the procedure that starts only if the results from Risk Assessment phase are considered not acceptable from the stakeholder. If the results from the first phase of the Procedure agree with the acceptance criteria, no action of intervention is required and risk treatment is not necessary. For this reason, the definition of acceptance criteria has first priority.

6.1 Acceptance criteria

As widely explained in chapter 4, the final user of the procedure is the manager of historical heritage buildings; it is hence necessary to adopt criteria suitable to his necessity of manager. Risk Assessment Method produces, for the three Objectives, risk indexes expressed in the risk scale proposed in Table 5.3. It is important to underline how risk indexes coming from the procedure have no absolute reference, they are not expressed calibrating the scale on the base of fire codes. An absolute calibration of the risk scale is not possible for the buildings we treat and for the Policy (protection of Valuable Contents) we want to reach. There are not minimum prescriptions or codes referring to protection against fire of contents in historical buildings in Italy, as referred in 4.2. No relationship exists therefore between the risk scale definition in Table 5.3 and fire codes application. This is the reason why, in this Procedure, acceptance criteria are mainly *building and contents dependent*.

The manager have to state which is the level of risk he can accept basing such decision on the importance and on the value both of the building and the contents. An evaluation of "importance" and "value" of Works of Art and Heritage Buildings is, as referred in Cost C17 [87, 88, 86], a complex issue that lies outside this text. Only art historians and conservers have enough competence to state such semi-philosophical concepts; in the follow some suggestions, in order to take a coherent set of acceptance criteria for the Objectives, are just proposed, according to the risk scale used in the Procedure.

Acceptance criteria should be based on two limit thresholds, as a lot of best practices used in risk assessment according to Italian D.Lgs. 81/08 [29]. A lower limit, defined as the value under which the building and its contents are in a positive situation has to be identified. Then an upper limit has to be defined, in order to state that over such risk value it is compulsory to take mitigation measures for risk reduction. An "action area", included between lower and upper limit, is this way created; that is the area within which it is expected to find the majority of the buildings. With such two limits, it is possible to reward virtuous managers that have indexes lower than lower limit and to penalize managers that exceed the upper risk limit. All the managers that have buildings with risk indexes under the lower limit aren't obliged to act in risk mitigation; if the building is in the "action area", managers can decide to act in order to have advantages in risk prevention. The area from 0 to the upper limit is defined as the "acceptable area"; if risk indexes are bigger than upper limit, the building is in the "not acceptable area" and the mitigation becomes compulsory.

Referring to Table 5.3, index *"5: risk condition"* is the midpoint of the scale. Around this midpoint it is suggested to create the "action area" described above. In the follow and in chapter 7 the following limits have been chosen:

- lower limit = 4;
- upper limit = 5,5.

and consequently:

- Acceptable area: $0 \leq risk\ index \leq 5,5$;
- Not acceptable area: $risk\ index > 5,5$;
- Action area: $4 \leq risk\ index \leq 5,5$.

Between 4 and 5,5 it is necessary to take mitigation measures to reduce risk as much as possible with the aim to decrease till 4. Over 5,5 limit, it is important to act immediately in order to reduce risk under 5,5.

It is suggested in the Procedure to fix lower limit at 4, according to the risk scale. Upper limit is mobile; by increasing and decreasing its value it is possible to create a wider or smaller "action area" and consequently "acceptable area", according to the importance of contents and building.

Risk indexes coming out from the Risk Assessment Method are referred both to the External Characteristics and to the Internal ones. It is possible to create a different "acceptability area" for External and Internal Characteristics, and different limits also for the various sectors, depending on the relative importance of the contents inside them. This means that the user can accept different levels of risk for the building from a global viewpoint (External Characteristics) and for the sectors composing the building itself (Internal Characteristics).

Since historical buildings and Valuable Contents are unique, in order to have a full scale it is necessary to refer it to the same building and contents. A relative representation of risk indexes can so be performed running twice the Risk Assessment Method: once for the actual situation of survey and once inserting data corresponding to the best situation we can reach in that specific building. Performing Risk Assessment Method twice for the building and twice for each sector, makes the user able to evaluate how distant actual risk indexes are with respect to the best risk indexes one can obtain in that historical building. A full explanation about this methods of risk communication and outcome representation is given in paragraph 6.3.2.

In the case studies presented in this dissertation, the same “acceptability area” has been defined for all the output evaluation. This choice has been made in order to make easier the comparison among indexes coming out from analysis performed on different buildings.

6.2 Measures of Mitigation

The main goal of the Risk Treatment Method is to provide indications on how to reduce risk for Valuable Contents. On the base of sensitivity analysis outcomes reported in chapter 5, it was possible to associate to each Objective the corresponding set of Characteristics that have more influence on the Objective itself. With the same process, to each Characteristic the most influencing Factors with respect to the chosen Objective were associated. In the end it was possible to arrive to the last step of the hierarchic structure, reaching the Sub-factors. The measures of mitigation are then associated to each Sub-Factors: this way, once chosen by the stakeholder the Objective to be mitigated, it is possible to descend the hierarchic structure along links of relative influence, form Characteristics to Sub-Factors, till arriving to the associated mitigation measures.

In linking levels of the hierarchic structure, basing on the results of sensitivity analysis, all the elements that had influence percentage lower than 20% were neglected. This way paths to be followed to mitigate a particular Objective, leading the user from the top of the structure till the lower level, the level of mitigation measures, were created. Each path for mitigation starts from an Objective and arrives to a package of measures of mitigation that are effective to reduce risk. In the follow the sub-hierarchy structures for mitigation both for the External and for the Internal Characteristics are depicted.

External Characteristics

Objective 1: Evacuation

Figure 6.1 shows the path from OB1 to the most effective measures of mitigation for External Characteristics. Intervention on EC2 has priority on intervention on EC1.

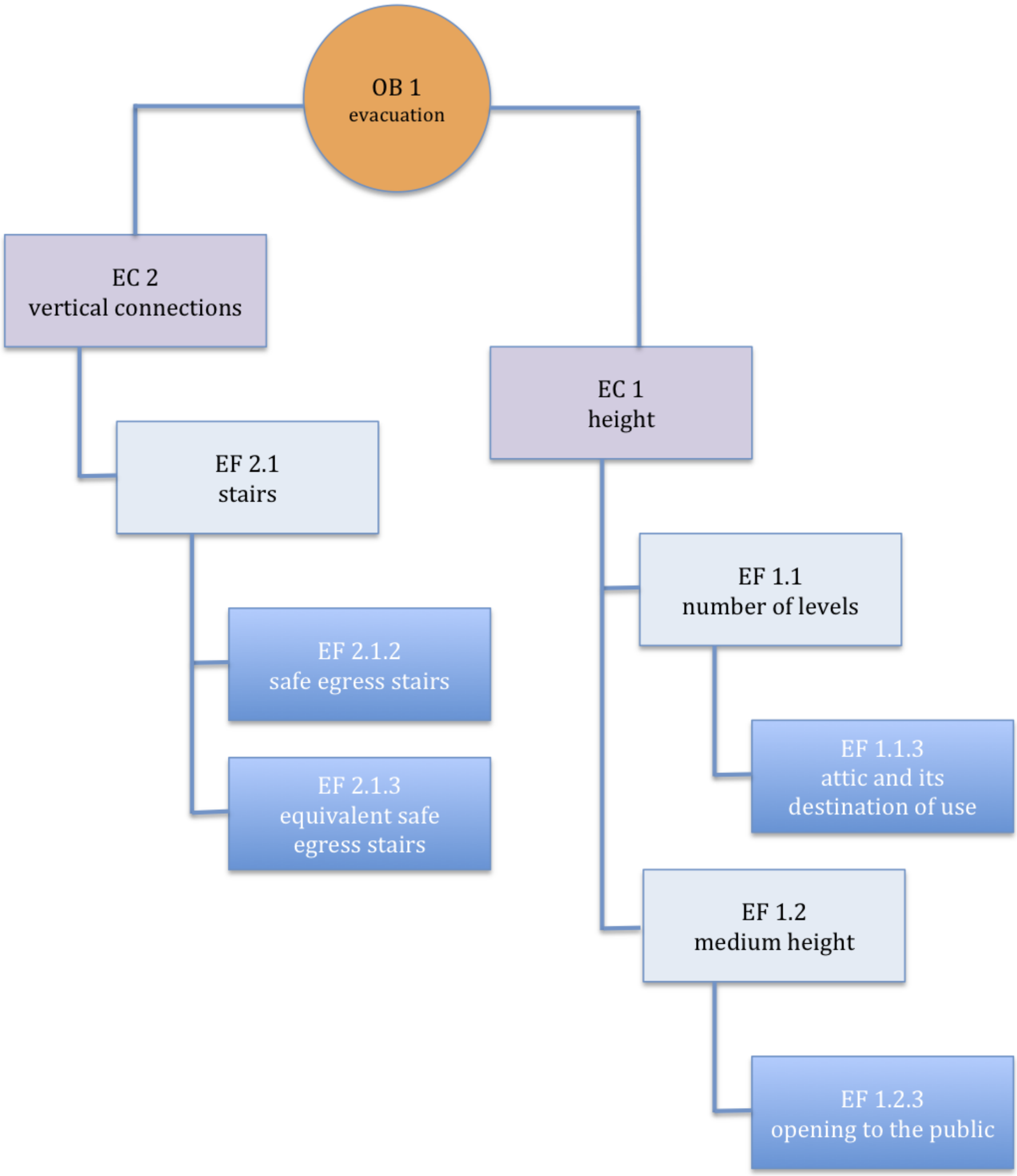


Figure 6.1: Sub-hierarchy structure for mitigation of Objective 1 with respect to the External Characteristics.

Objective 2: Fire brigade effectiveness

Figure 6.2 shows the path from OB2 to the most effective measures of mitigation for External Characteristics.

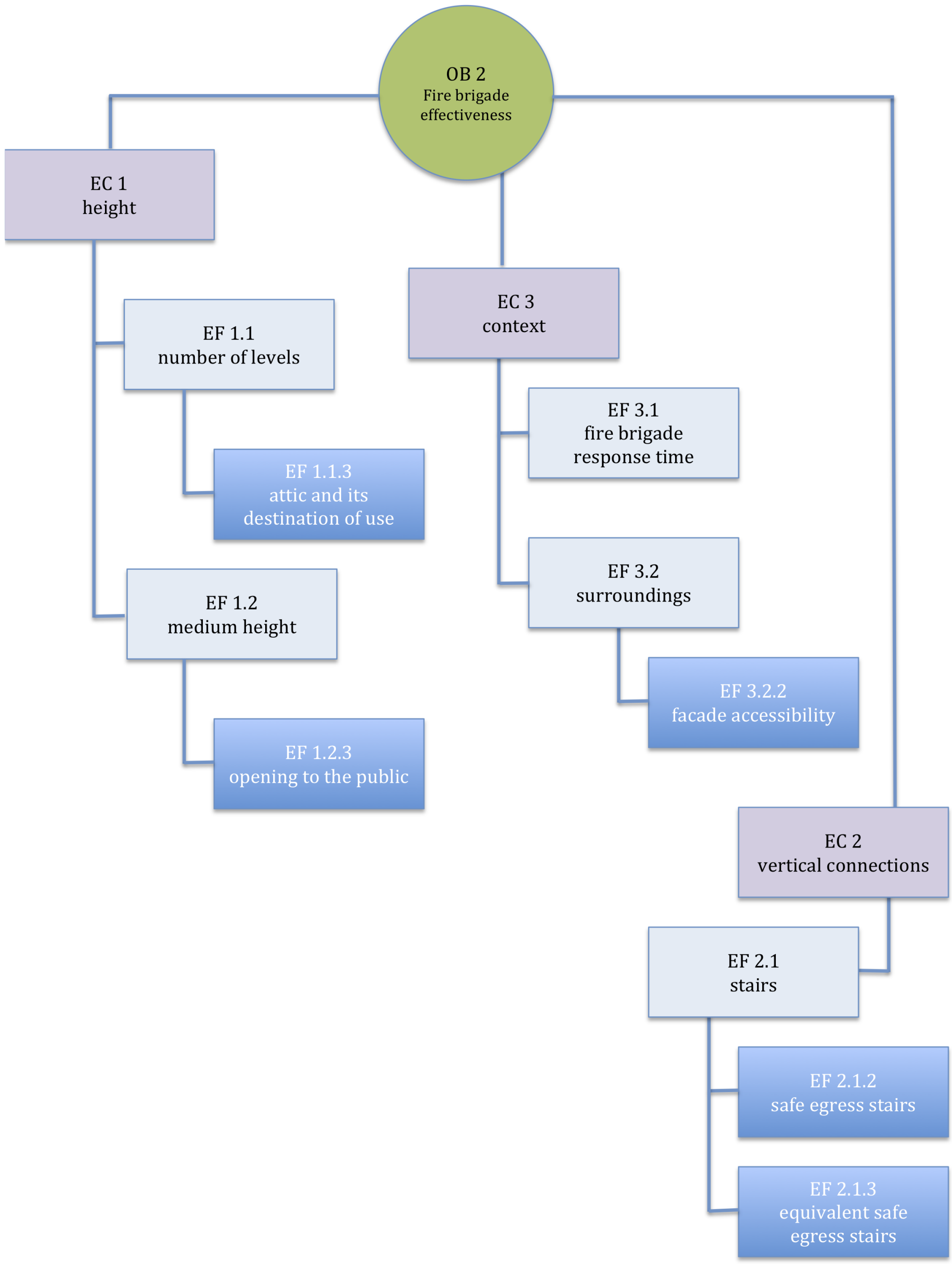


Figure 6.2: Sub-hierarchy structure for mitigation of Objective 2 with respect to the External Characteristics.

Objective 3: Fire and smoke spread

Figure 6.3 shows the path from OB3 to the most effective measures of mitigation for External Characteristics.

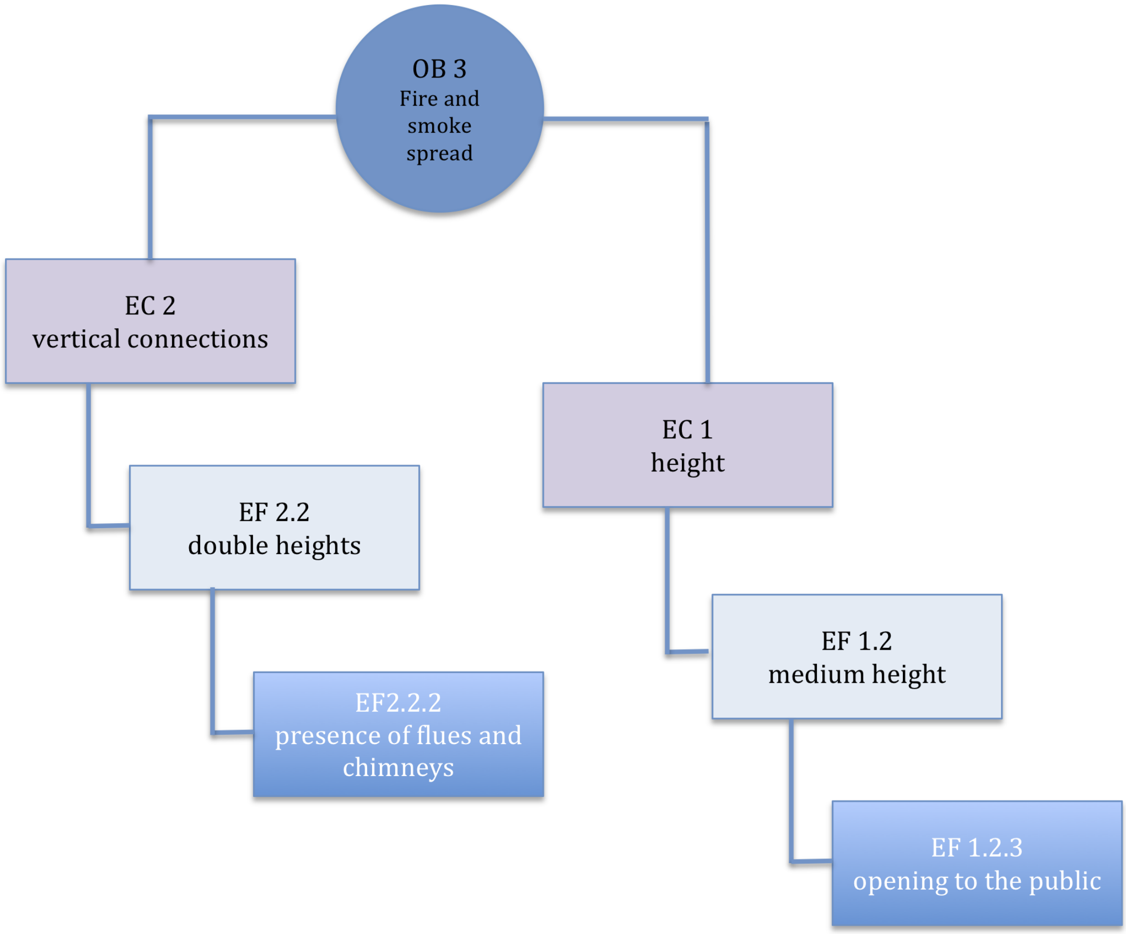


Figure 6.3: Sub-hierarchy structure for mitigation of Objective 3 with respect to the External Characteristics.

Internal Characteristics

Objective 1: Evacuation

Figure 6.4 shows the path from OB1 to the most effective measures of mitigation for Internal Characteristics.

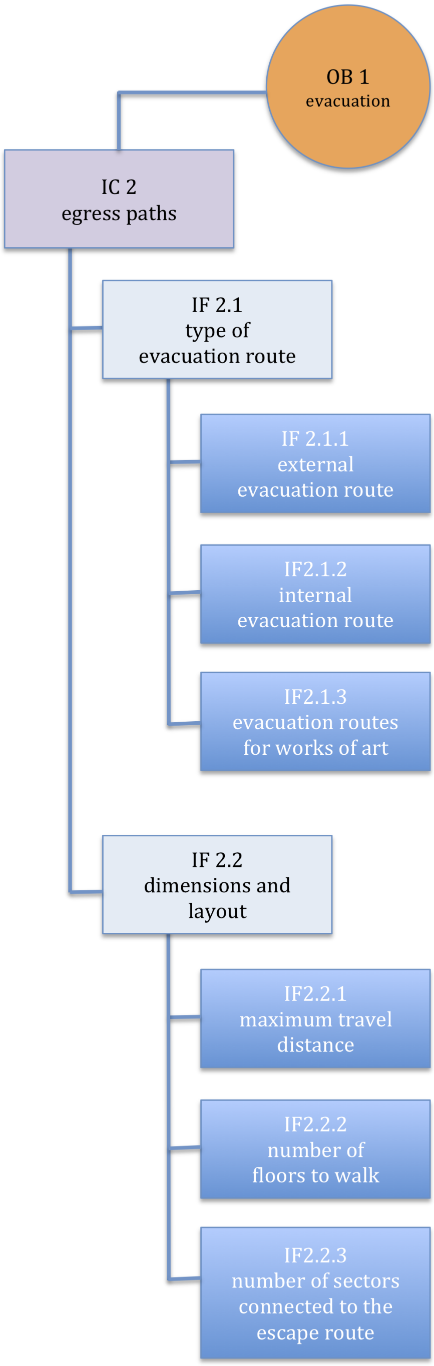


Figure 6.4: Sub-hierarchy structure for mitigation of Objective 1 with respect to the Internal Characteristics.

Objective 2: Fire brigade effectiveness

Figure 6.5 shows the path from OB2 to the most effective measures of mitigation for Internal Characteristics.

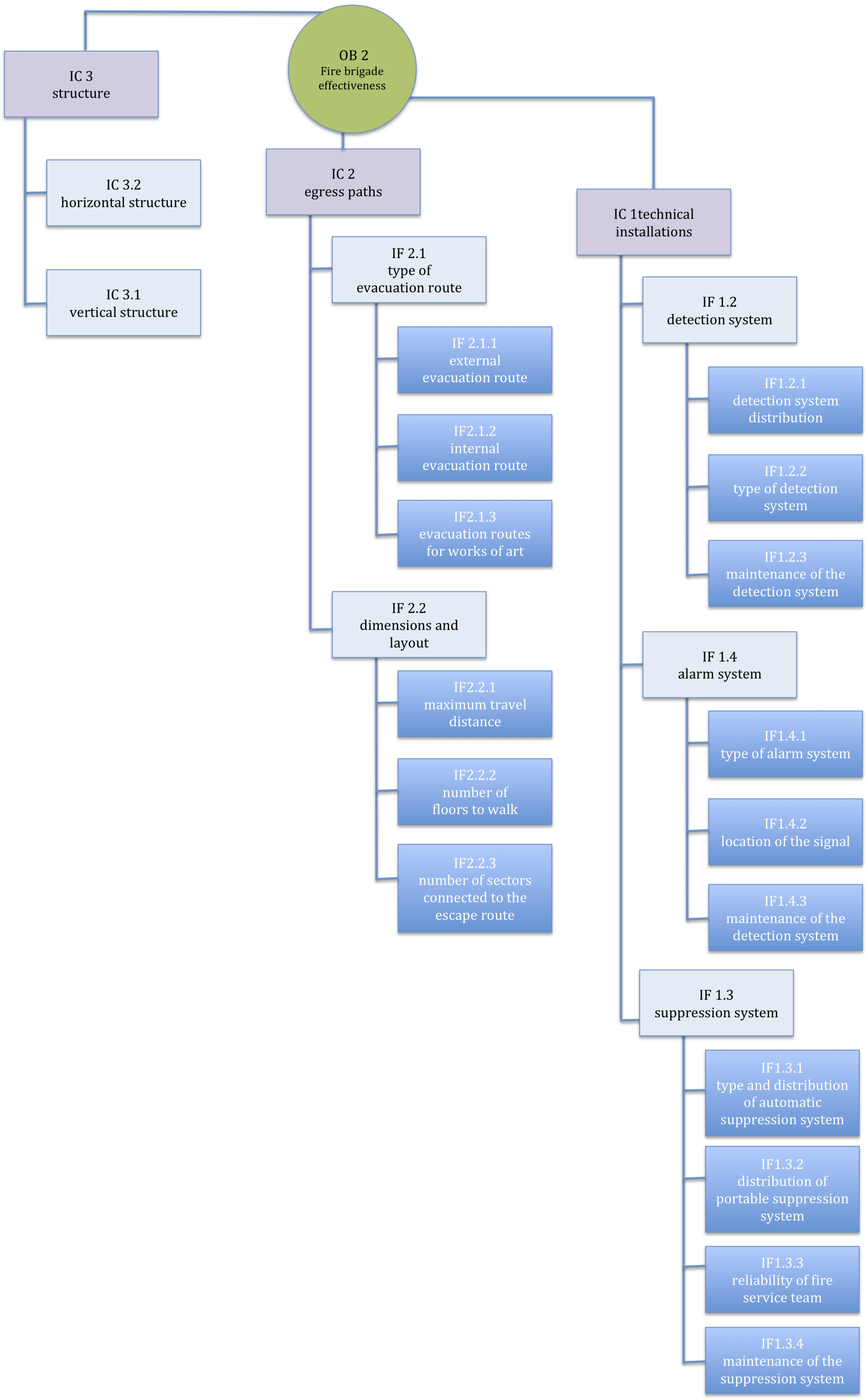


Figure 6.5: Sub-hierarchy structure for mitigation of Objective 2 with respect to the Internal Characteristics.

Objective 3: Fire and smoke spread

Figure 6.6 shows the path from OB3 to the most effective measures of mitigation for Internal Characteristics.

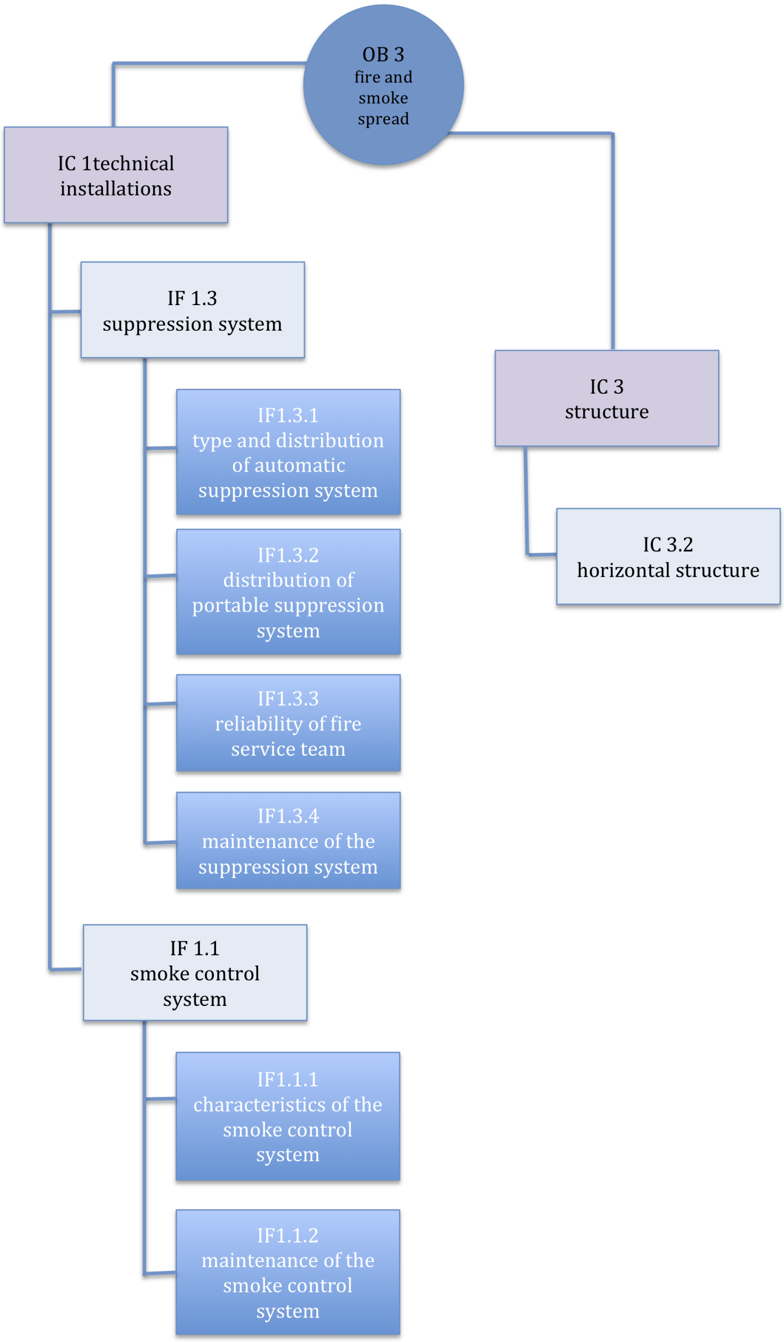


Figure 6.6: Sub-hierarchy structure for mitigation of Objective 3 with respect to the Internal Characteristics.

Mitigation measures are strictly linked, as said, to the Sub-Factors. To give more effective indications to the user, every mitigation measure belongs to one of the two following categories, defined on the base of the "cost" of the measure:

- **Management Strategies**
  These measures of mitigation are intended to be at "zero cost" or at least at a lower cost than the measures in the other category. Management Strategies are the measures that a manager can adopt without the necessity of an intervention on the building fabric. This measures are usually to be preferred in risk mitigation because it is more probable to be able to act on the management, instead of on the architerctonic configuration of the building.

- **Building intervention Strategies**
  These measures of mitigation are intended to be costly, or at least at an higher cost than the measures in the other category. In this category all the measures that necessarily modify the building are comprehended: installations of technical devices, intervention on the building's structure, on the facades, on the vertical connections and so on. Such measures often cannot be avoided to have a good performance in Valuable Contents protection, but they are very difficult to be fully implemented because of problems of compatibility and intervention on historical buildings.

In Table 6.1 all the mitigation measures associated to Sub-Factors for External Characteristics are described. In Table 6.2 all the mitigation measures associated to Sub-Factors for Internal Characteristics are described. If some Sub-Factors are not in the table, it means that no mitigation measures can be associated to them.

Factor	*Sub-Factor*	*Mitigation Mesure*	*Category of Mitigation Measure*
IF1.1 Smoke control system	IF1.1.1 characteristics of the smoke control system	It could be possible to intervene modifying or installing the smoke control system	Building intervention
	IF1.1.2 maintenance of the smoke control system	It is possible for the building's manager to forecast regular the maintenance	Management
IF1.2 Detection system	IF1.2.1 detection system distribution	It could be possible to intervene modifying or installing the detection system	Building intervention
	IF1.2.2 type of detection system	It could be possible to intervene modifying the type of the detection system	Building intervention
	IF1.2.3 maintenance of the detection system	It is possible for the building's manager to forecast regular the maintenance	Management
IF1.3 Suppression system	IF1.3.1 type and distribution of automatic suppression system	It could be possible to intervene modifying or installing the automatic suppression system	Building intervention
	IF1.3.2 distribution of portable suppression system	It is possible for the building's manager to increase the number of portable suppression equipment and its distribution	Management

	IF1.3.3 reliability of fire service team	It is possible for the building's manager to increase the quality of the fire service team acting on the number of components and their formation (ref. to FSI)	Management
	IF1.3.4 maintenance of the suppression system	It is possible for the building's manager to forecast regular the maintenance	Management
IF1.4 Alarm system	IF1.4.1 type of alarm system	It could be possible to intervene modifying or installing the alarm system	Building intervention
	IF1.4.2 location of the signal	It could be possible to intervene modifying the location of the signal	Building intervention
	IF1.4.3 maintenance of the detection system	It is possible for the building's manager to forecast regular the maintenance	Management
IF2.1 Type of Evacuation Route	IF2.1.1 external evacuation route	It could be possible to intervene modifying the external evacuation route system	Building intervention
	IF2.1.2 internal evacuation route	It could be possible to intervene modifying the internal evacuation route system	Building intervention
	IF2.1.3 evacuation routes for works of art	It is possible for the building's manager to change the Damage Limitation Plans avoiding dangerous paths for works of art	Management
IF2.2 Dimension and Layout	IF2.2.1 maximum travel distance	It could be possible to modify the maximum travel distance with heavy structural intervention	Building intervention
	IF2.2.2 number of floors to walk	It could be possible to modify the number of floors to walk with heavy structural intervention (stairs, protected elevators...)	Building intervention
	IF2.2.3 number of sectors connected to the escape route	It could be possible to modify the number of sectors connected with the egress path with heavy structural intervention (stairs, protected elevators...). It is further possible to take management strategies that allow to reduce the number of sectors linked with that specific egress path	Management and Building intervention
IF2.3 Linings and Floorings	IF2.3.1 type of lining and floorings	It could be possible to modify linings and floorings in egress paths	Building intervention
IF3.1 Vertical Structure	IF3.1.1 vertical structure	It could be possible to intervene on the structure to improve its resistance according to fire codes	Building intervention
IF3.2 Horizontal Structure	IF3.1.1 horizontal structure	It could be possible to intervene on the structure to improve its resistance according to fire codes	Building intervention

Table 6.2: Measures of mitigation linked with Internal Factors.

Factor	*Sub-Factor*	*Mitigation Mesure*	*Category of Mitigation Measure*
EF1.1 Number of Levels	EF1.1.3 attic and its destination of use	It is possible for the building's manager to change the destination of use of the attic	Management
EF1.2 Medium Height	EF1.2.3 opening to the public	It is possible for the building's manager to modify the opening to the public of the interested building's area	Management
EF2.1 Stairs	EF2.1.2 safe egress stairs	It could be possible to intervene on the stairs to make them "safe" according to the fire codes	Building intervention
	EF2.1.3 equivalent safe stairs	It could be possible to intervene on the stairs to make them useful for the emergency paths	Building intervention
EF2.2 Double Heights	EF2.2.2 presence of flues and chimneys	It could be possible to intervene sealing all the vertical connections among the levels of the building	Building intervention
EF3.1 Fire Brigade response time	EF3.1.1 fire brigade response time	It is possible for the building's manager to take special agreements with fire brigades in order to reduce their intervention time	Management
EF3.2 Surroundings	EF3.2.2 facade accessibility	It could be possible to intervene modifying the openings in the facades in order to make them easier accessible from the extern	Building intervention

Table 6.1: Measures of mitigation linked with External Factors.

6.3 Risk communication: how to display results

Risk communication is an interactive process of exchange of information and opinions on risk among risk assessors, risk managers, and other interested parties. In this dissertation the most important goal is to communicate risk to the manager of historical buildings, that is the stakeholder with a low risk-confidence.

As reported in literature [31, 90, 53], risk communication is an integral and ongoing part of the risk management exercise, and ideally all the stakeholder groups should be involved from the start. Risk communication makes stakeholders aware of the process at each stage of the Risk Management. This helps to ensure that the logic, outcomes, significance, and limitations of the Risk Assessment are clearly understood by all the stakeholders.

The identification of particular interest groups and their representatives should comprise a part of an overall risk communication strategy. This risk communication strategy should be discussed and agreed between risk assessors and managers early in the process, in order to ensure two-way communication. In this dissertation, the addressees of the risk communication are the managers of historical buildings, persons that basically also are, at the same time, risk managers for their buildings. Usually buildings' managers are not expert in risk management but they are the persons who have the duty to act in order to reduce risk for Valuable Contents. The Risk Management Procedure of this dissertation have to communicate risk to "not risk-confident" stakeholder that, basing on the procedure's suggestion, have to act as risk manager in mitigating risk.

Decisions on risk communication, including what, whom and how, should be part of an overall risk communication strategy. Risk communication is most effective if undertaken in a systematic way, and generally starts with the gathering of information on the risk issue of concern. Therefore the risk manager and risk assessor must be able to briefly and clearly summarize what this issue encompasses, at an early stage, in order to elicit interest and stakeholder input Communication must then continue throughout the entire process.

The fundamental goal of risk communication is to provide meaningful, relevant and accurate information, in clear and understandable terms targeted to a specific audience. It may not resolve all the differences between the parties, but may lead to a better understanding of those differences. It may also lead to more widely understood and accepted risk management decisions. Effective risk communication should have goals that build and maintain trust and confidence. It should facilitate a higher degree of consensus and support by all interested parties for the risk management option(s) being proposed.

From [31], the goals of risk communication are here reported:

1. Promote awareness and understanding of the specific issues under consideration during the risk analysis process, by all participants;

2. Promote consistency and transparency in arriving at and implementing risk management decisions;

3. Provide a sound basis for understanding the risk management decisions proposed or implemented;

4. Improve the overall effectiveness and efficiency of the risk analysis process;

5. Contribute to the development and delivery of effective information and education programmes, when they are selected as risk management options;

6. Strengthen the working relationships and mutual respect among all participants;

7. Promote the appropriate involvement of all interested parties in the risk communication process;

8. Exchange information on the knowledge, attitudes, values, practices and perceptions of interested parties concerning risks and related topics.

Basing on this concept, strong importance was assigned to the methodology of representation for the risk results from Risk Assessment Method. Risk Indexes, with respect to the three Objectives, are shown by means of different graphs and tables. In the following paragraphs different ways to represent outcomes from Risk Assessment Method are shown.

6.3.1 Absolute representation of risk

This way of representing results is the most intuitive and immediate. Risk indexes are depicted in histograms and the "action area" is identified by means of two horizontal lines corresponding to its boundary (red line corresponds to upper limit 5,5 and green line corresponds to lower limit 4). In Figure 6.7 an example of such representation is given.

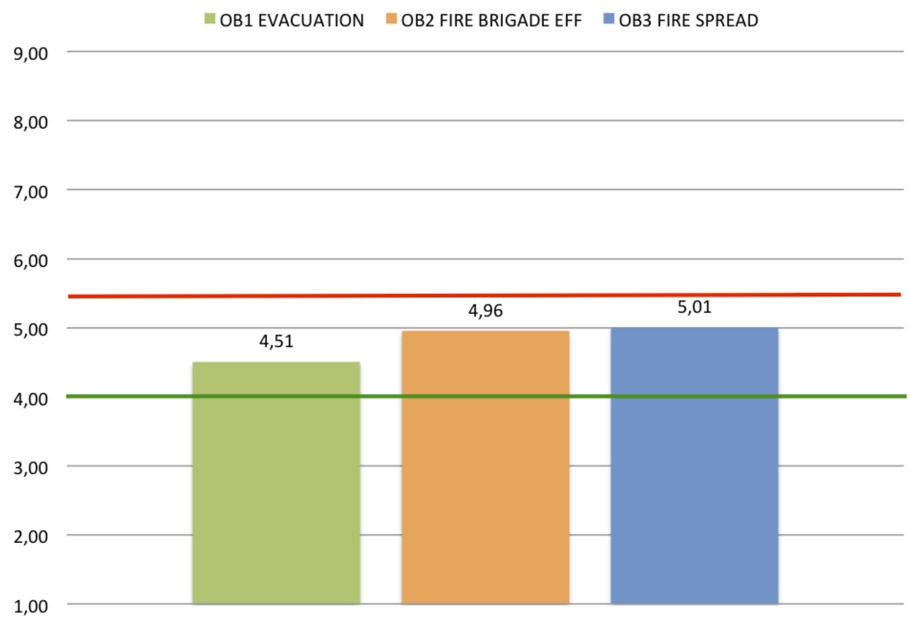


Figure 6.7: Example of absolute representation of the risk indexes for the three Objectives.

6.3.2 Relative representation of risk

Relative representation of risk indexes is referred to the full scale created *ad hoc* for the analysed building, as described on page 149. Risk Assessment Method has been run once for the actual situation of survey and once inserting data corresponding to the best situation reachable in that specific building. Outcomes of Risk Assessment Method are, in this case, information as the ones reported in Table 6.4.

	Best Index	*Risk Index*	*Level of Mitigation Measures*
OB1	2,09	4,51	46%
OB2	3,05	4,96	62%
OB3	1,10	5,01	82%

Table 6.3: Example of information from Risk Assessment Method useful for relative representation of risk indexes.

In Table 6.4:

- *Best index* = *BI*; first column represents the risk index one can reach in that building by the full implementation of the mitigation measures suitable for that specific situation;
- *Risk index* = *RI*; second column represents the risk index coming from the evaluation of the actual situation in the building;
- third column represents level of application of the mitigation measures. Such pa-

rameter is defined as

$$LMM = \frac{BI}{RI} \tag{6.1}$$

and says "how much" has been done in fire prevention with respect to what is possible to do in the future. The higher such parameter is, the less it is possible to do in risk mitigation; this is the case in which RI in quite near to BI.

From above described information, it is possible to represent data in graphs like the one in Figure 6.8: on the x axis the risk scale according to Table 5.3 is reported and on y axis LMM parameter is reported; points are identified by coordinates (RI; LMM). Vertical red line corresponds to the upper risk limit, vertical green line corresponds to the lower limit of the "action area", as defined in paragraph 6.1.

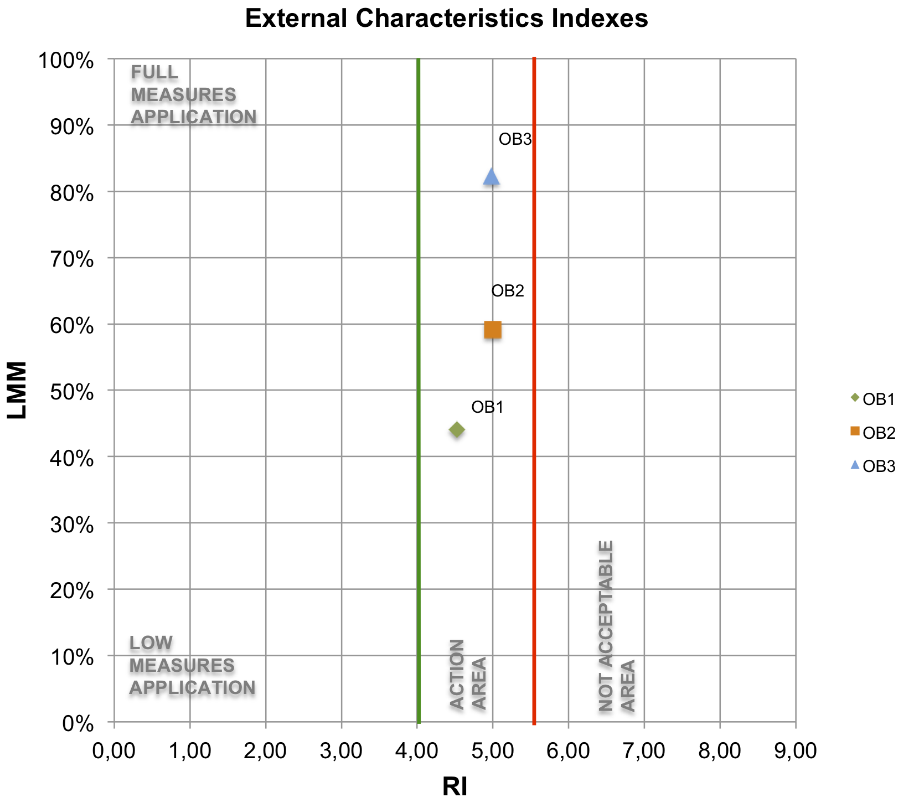


Figure 6.8: Example of relative representation of the risk indexes for the three Objectives.

The virtuous situation is when all the points are below than the lower limit and in the upper part of the graph, that means very low risk and full implementation of measures of mitigation.

The worst situation is for points with risk indexes higher than upper limit and in the upper part of the graph. This means that, despite the high risk, there are not mitigation measures to be taken in order to reduce risk.

The most common situation is to have points that, apart from their risk index, are in the middle area of y axis; this means that there are enough mitigation measures to be taken.

The relative representation can be used to choose which is the Objective the manager wants to mitigate first: Objectives with high risk index and low level of MMT are to be preferred.

The relative representation can be useful also to depict risk indexes after Risk Treatment phase, to communicate to the manager the efficacy of his actions of mitigation. Following procedure described in section 6.2, from the Procedure are obtained risk indexes associated to the behaviour of the building after the application of specific mitigation measures. Parameters used for graphic representation are the same shown above; risk indexes are now calculated after the application of suitable mitigation measures. While BI doesn't change, a decreasing of RI is expected.

6.3.3 Representation of mitigation

In the *Risk Management Procedure for Valuable Contents in Historical Heritage Buildings*, a set of instructions to reduce risk are suggested as output of the Risk Treatment phase, as described in section 6.2. The final user of the procedure must be aware of which mitigation measure is most efficacy and why the Procedure suggests him to attempt a specific *mitigation path*. In this paragraph three different ways of representing risk with respect to the mitigation are given.

Triangle of mitigation

This is the most simple way to represent and to communicate risk and efficacy of mitigation. "Triangle representation" consists only in depicting the three risk indexes, one for each Objective, on a 3 axis graph. Each set of three points depicts a triangle that defines the status of the situation with respect to which indexes are calculated. The external triangle represents the risk upper limit and no other point should exceed its boundary. The inner triangle represents the best situation; all the other sets of indexes are outside of its perimeter. Between inner and outer triangles, there is the shape representing the actual situation. Also after mitigation, the situation can be depicted; in this case, the corresponding triangle is expected to be internal to the one of the actual situation. In Figure 6.9 and 6.10 examples of "triangle representation" are given.

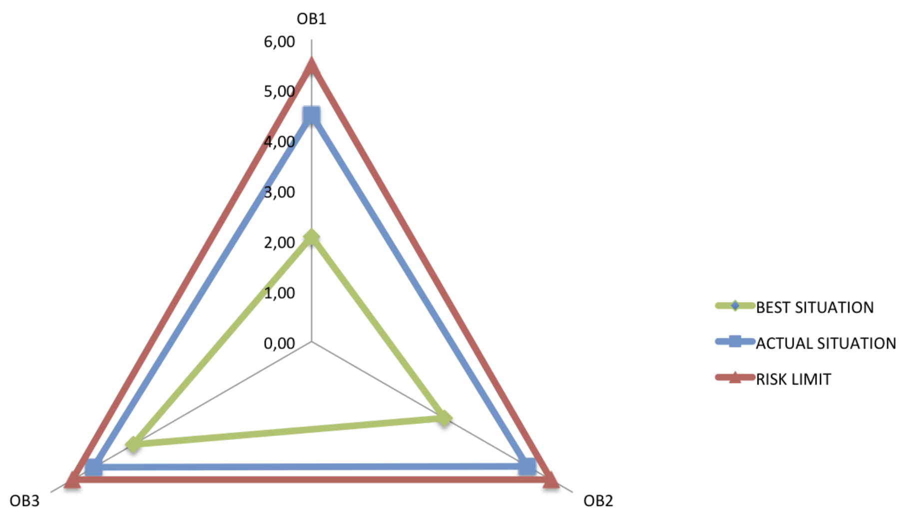


Figure 6.9: Example of relative "triangle representation" for the actual situation.

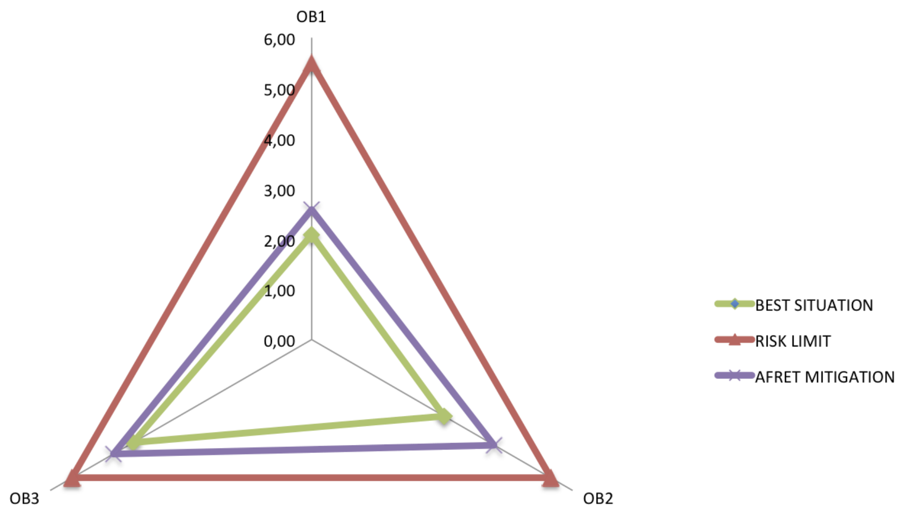


Figure 6.10: Example of relative "triangle representation" for the situation after mitigation.

Paths of mitigation

By this kind of representation the milestones the user has to reach in order to mitigate risk in the building he manage are shown. The proposed representation is not referred to the absolute risk index representation; it is possible this way to choose every suitable upper risk limit and not to loose sense in output representation. Upper risk limit (RL) is here considered together with two additional parameters:

$$\Delta R = RL - RI \tag{6.2}$$

that measures the distance between the actual situation and the risk upper limit, and

$$MMT = 1 - LMM \tag{6.3}$$

that is an estimation of the Mitigation Measure that can be taken with respect to the ones adopted in the actual situation (LMM). Parameters are calculated as output of the procedure and are resumed in tables like Table 6.4, here reported as an example.

		Actual situation	*After mitigation*	*Best situation*
OB1	ΔR	0,99	2,92	3,41
	MMT	54%	19%	0%
OB2	ΔR	0,54	1,31	2,45
	MMT	38%	27%	0%
OB3	ΔR	0,49	0,95	1,40
	MMT	18%	10%	0%

Table 6.4: Example of parameters useful for *mitigation paths* representation.

The parameters calculated for the actual situation in the building are in the first column; these parameters come out from the first application of the Risk Assessment Method on the building, once collected the starting data.

The parameters calculated for the best situation we can have in that specific building are in the third column. This is the reason why parameters MMT (Mitigation Measures to be Taken) are equal to zero; we assume that, in the best situation, we have a full implementation of mitigation measures.

Indexes calculated after the application of a package of mitigation measures, according to indications given in section 6.2, are in the second column.

By means of such parameters graphs like Figure 6.11 are depicted. In such kind of graphs, the level of Mitigation Measure to be Taken decreases while the ΔR parameter, indicating how far we are from the not acceptable risk limit, increases. User can read which are the paths he can follow, applying the mitigation packages in section 6.2, to reach the best situation for the building. Such graphs can be built once chosen the Objective to be mitigated and it represents also the secondary effect of mitigation we have on the other two Objectives, not directly interested by actions of mitigation.

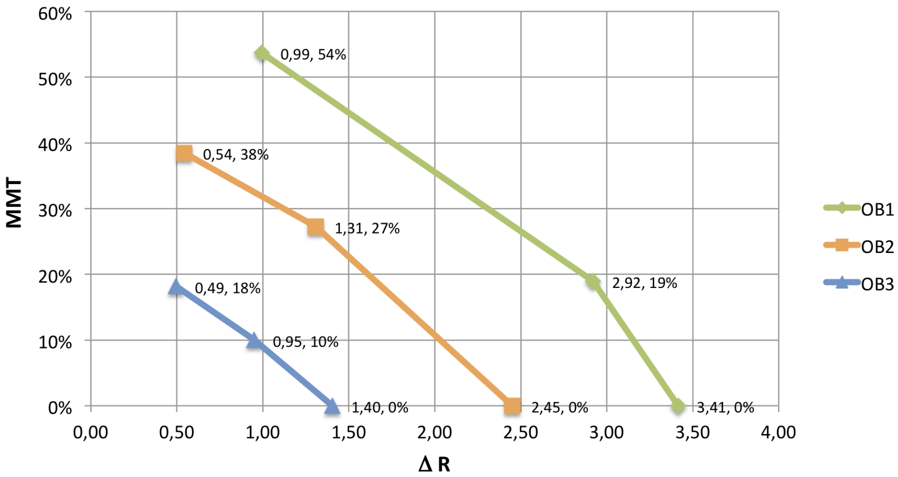


Figure 6.11: Example of *mitigation paths* representation for the three Objectives.

Area of mitigation

From the representation of "paths of mitigation", it is evident that mitigation trend is quite linear. "Area of mitigation" represents just the plot of ΔR over MMT for the actual situation and for the best situation. By means of this representation, the area of the triangle under the broken line gives a qualitative impression about the possibility to mitigate risk in that building. The bigger is the area under the line, the more is possible to act in order to reduce risk, and that can be done using the paths of mitigation.

The representation with "area of mitigation" is mainly useful to the building's manager when he has to manage more than one building. By means of this graphs it is possible to join, on the same figure, areas representing different buildings. This can be done comparing corresponding Objectives: a comparison of the same Objective with respect to External Characteristics of the two buildings or a comparison of the same Objective with respect to Internal Characteristics of sectors of each building with highest risk index. Such comparison can be done whatever is the chosen upper risk limit, in the representations in fact only dimentionless parameters are involved.

A manager that has to decide which one of the building he manages needs priority in intervention and "how much" he can act in risk reduction, has just to decide a comparison Objective ad to look at "area of mitigation" graphs. In Table 6.5 sample data for two buildings, useful to depict "area of mitigation" graphs like Figure 6.12 are shown.

		Actual situation	*Best situation*
Building 1	ΔR	0,99	3,41
	MMT	54%	0%
Building 2	ΔR	1,74	1,99
	MMT	7%	0%

Table 6.5: Example of parameters useful for "area of mitigation" graphs for two buildings with respect to one fixed Objective.

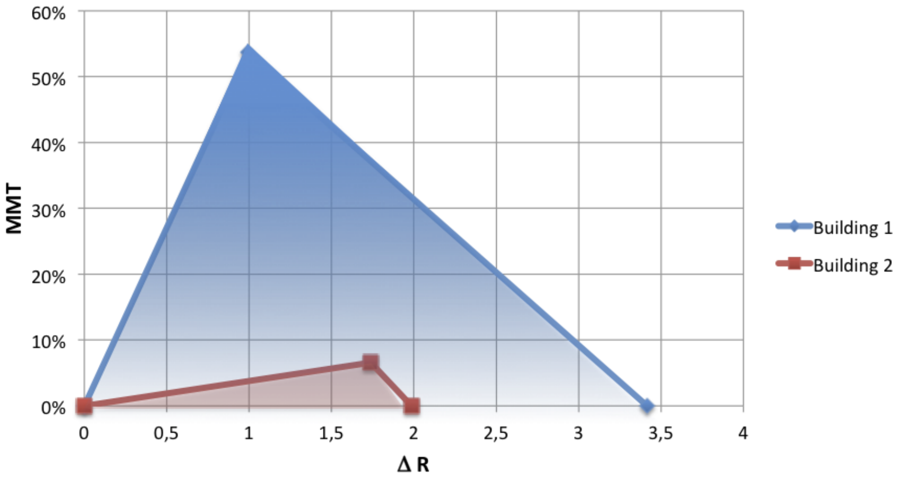


Figure 6.12: Example of "area of mitigation" graphs for two buildings with respect to one fixed Objective.

Figure 6.12 shows in a qualitative way how small the leeway is in acting on building 2 while building 1 allows to take more mitigation measures in order to reduce risk till the best situation.

Chapter 7

Case Studies

In this chapter two application examples of the Risk Management Procedure are shown. Procedure was run applying it to two historical buildings in Tuscany: Opificio delle Pietre Dure base in Fortezza da Basso in Firenze and Palazzo Chigi Saracini in Siena. The two buildings have been chosen to test the Procedure in real buildings with known characteristics with respect to the fire protection. Opificio delle Pietre Dure building in Fortezza da Basso is the base of one of the most important conservation laboratories for works of art in Europe. The building that hosts the laboratory is inside Fortezza da Basso in Firenze, the building has a very simple architectonic configuration despite the complexity of the activity conducted inside it. In the building the most important masterpieces of Art History to be conserved are temporary placed (but for long periods of time). Contents of the building are estimated to be some of the most important masterpieces all over the world. For this reason in the building technical installations for fire prevention and protection are suitable, as well as the staff is well trained in contents protection against fire and evacuation.

Palazzo Chigi Saracini is one of the most important building of Siena historic centre; it is a complex building with a lot of different activities inside it. Despite such architectonic complexity, almost no permanent fire protection or prevention measure is applied at the moment. The approval of the fire protection design is in progress at the moment. In the building valuable contents (works of art and musical instruments) that are precious and to be preserved are contained.

In table 7.1 a resume of the features characterizing the two buildings is shown.

Opificio delle Pietre Dure	*Palazzo Chigi Saracini*
Simple architectonic configuration	**Complex** architectonic configuration
Building containing **masterpieces** of Art History	Building containing **valuable assets**
Very good **technical installations** for fire protection and prevention	Almost total **absence of technical systems** for fire protection and prevention

Table 7.1: Features characterizing the two buildings.

7.1 Opificio delle Pietre Dure

In this chapter the results deriving from the application of the risk management procedure to an historical building in Florence are presented. The building analysed is the "Opificio delle Pietre Dure" base inside the Fortezza da Basso in Firenze.

Opificio delle Pietre Dure e Laboratori di Restauro is a public institute of the Italian Ministry for Cultural Heritage based in Florence. It is a global leader in the field of art restoration and provides teaching as one of the two Italian state conservation schools (the other being the Istituto Superiore per la Conservazione ed il Restauro). The institute maintains also a specialist library and archive of conservation and a museum displaying historic examples of Pietre Dure inlaid semi-precious stones artefacts. A scientific laboratory conducts research and diagnostics and provides a preventive conservation service [47].

Being one of the famous artistic workshops of the Italian Renaissance, the Opificio was established in 1588 at the behest of Ferdinando I de' Medici to provide the elaborate, inlaid precious and semi-precious stoneworks. One of the masterpieces of the crafts is the overall decoration of the Cappella dei Principi in the Basilica di San Lorenzo di Firenze. The technique, which originated from Byzantine inlay work, was perfected by the Opificio masters and the artworks they produced became known as "opere di Commessi Mediceo" (*commesso* is the old name of the technique, similar to ancient mosaics) and later as "Commesso in Pietre Dure" (semi-precious stones mosaic). The artisans performed the exceptionally skilled and delicate task of inlaying thin veneers of semi-precious stones especially selected for their colour, opacity, brilliance and grain to create elaborate decorative and pictorial effects. Items of extraordinary refinement were created in this way, from furnishings to all manner of artworks. Today, artisans trained at the Opificio assist many of the world's museums in their restoration programmes. The Opificio workshops were originally located in the Casino Mediceo, then in the Uffizi and were finally moved to their present location in Via Alfani in 1796. After the end of the XIX Century the institute's activities moved away from the production of works of art and towards its restoration. At first specialising in hardstone carving, in which the workshops were a world authority, and then later expanding into other related fields (stone and marble sculptures, bronzes, ceramics).

The second branch of the Institute (Laboratori di Restauro) had a more modern story. In 1932 Ugo Procacci, the distinghished scholar of Florentine art, in his career as an officer of the Italian Ministry for Cultural Heritage, founded a Laboratory of restoration (original Italian name: Gabinetto di Restauro) at the Florence Soprintendenza. It was the first modern restoration laboratory in Italy (pre-dating of 7 years the Istituto Superiore per la Conservazione ed il Restauro in Rome) and one of the very first ones in all the world. The Gabinetto di Restauro used scientific methods for the preliminary exhamination of the works of art (as X radiography) and began an outstanding campaign of restoration on Tuscan Early Masters paintings.

In 1966, the fatal tragedy of the flooding of the River Arno, resulted in many priceless works of art requiring restoration. It provided a significant impetus for expansion of the Gabinetto di Restauro's research and restorative services. More space was needed because of the sheer number of artworks which required restoration and also, in some cases, the large size of the pieces themselves, such as the immense Crucifix by Cimabue from the Basilica di Santa Croce. The expansions provided new laboratories in the Fortezza da Basso. Thanks to financial aid and an influx of expertise from throughout the world, the Florentine Laboratory became, in a short time one of the at the vanguard restoration laboratories in the world, combining traditional practices with modern technology. In 1975, the Cultural Heritage Ministry merged the Opificio laboratories with the Gabinetto di Restauro (plus other minor Florentine restoration laboratories) and created a new Institute, the modern Opificio delle Pietre Dure e Laboratori di Restauro. Today, the institute is organised in specific departments for the various types of artworks it treats. The laboratories are in three principal venues: in Via Alfani 78, in the historic centre of Florence; in the Fortezza da Basso; and in Palazzo Vecchio where restoration treatments on tapestries and textiles are carried out. There are also several research and services offices. The Opificio has a board of directors of the departments, under the supervision of the Soprintendente. It has also a management committee and a scientific committee. The Departments for conservations are:

- Tapestries and carpets
- Bronzes and ancient weapons
- Wooden Sculptures
- Wall Painting
- Drawings and Prints
- Stoneworks
- Pietre dure mosaics
- Jewelry
- Easel Paintings

- Terracotta and potteries
- Textiles

The building we studied was the Fortezza da Basso base, in Figure 7.1 the entrance of the building. This building hosts the departments of Wooden Sculptures, Wall Paintings, Drawings and Prints, Easel Paintings and Textiles. Inside the building there are also offices and laboratories.

Figure 7.1: Main entrance of the OPD building in Fortezza da Basso.

The building has rectangular shape and two stores height; the main vertical structure is composed of mansory and the floors and the roof are wooden-made. There are three main staircases, one of them fire protected. All the Figures here reported derive from Capone et al. [38]. In Figure 7.2 the Fortezza da Basso map is shown with a marker indicating the OPD base. In Figure 7.3 and 7.4 plans and sections of the building are shown.

To estimate the Internal Characteristics, the building has been divided into six sectors:

- Sector 1: it is located at the ground floor and it contains storage rooms and the photography laboratory;
- Sector 2: it is located at the ground floor and it contains the Easel painting department;
- Sector 3: it is located at the ground floor and it contains the Wooden Sculptures and Wall Painting departments;
- Sector 4: it is located at the ground floor and it contains carpentry and laboratories;
- Sector 5: it is located at the first floor and it contains Textile department and offices;

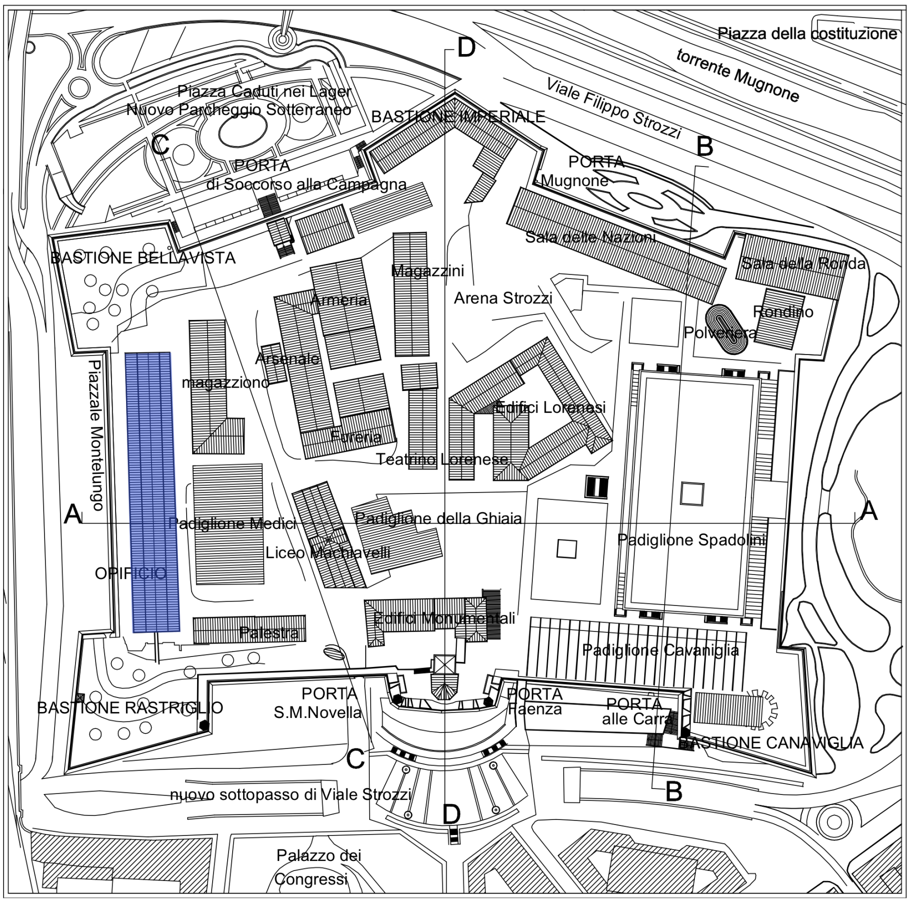


Figure 7.2: Map of the Fortezza da Basso with indication of OPD building.

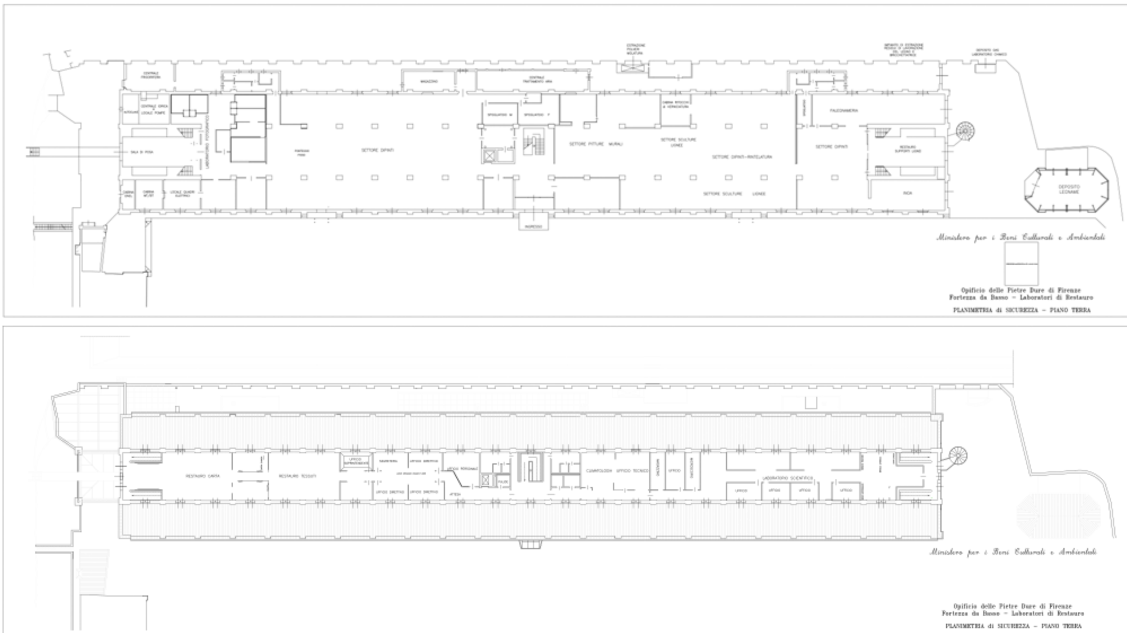


Figure 7.3: Ground floor and first floor of the OPD Building in Fortezza da Basso, [38].

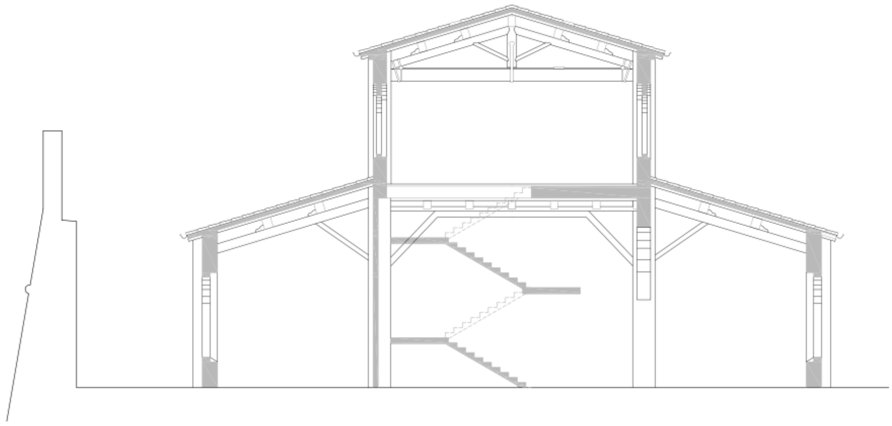


Figure 7.4: Section of the OPD Building in Fortezza da Basso, [38].

- Sector 6: it is located at the first floor and it contains laboratories and offices.

(refer to the Figure 7.5 to individuate them). The sectors correspond to the fire compartments into which the building is divided; the stairs in the center of the building are protected, while the other two stairs at the extremes of the building are common stairs made of stone. In the following, tables resuming the results from the procedure are reported for each sector and for the External Characteristics; in these tables there is also a brief description about the situation in the building. For each set of characteristics there are two tables, one referred to the actual situation and the other referred to the best situation.

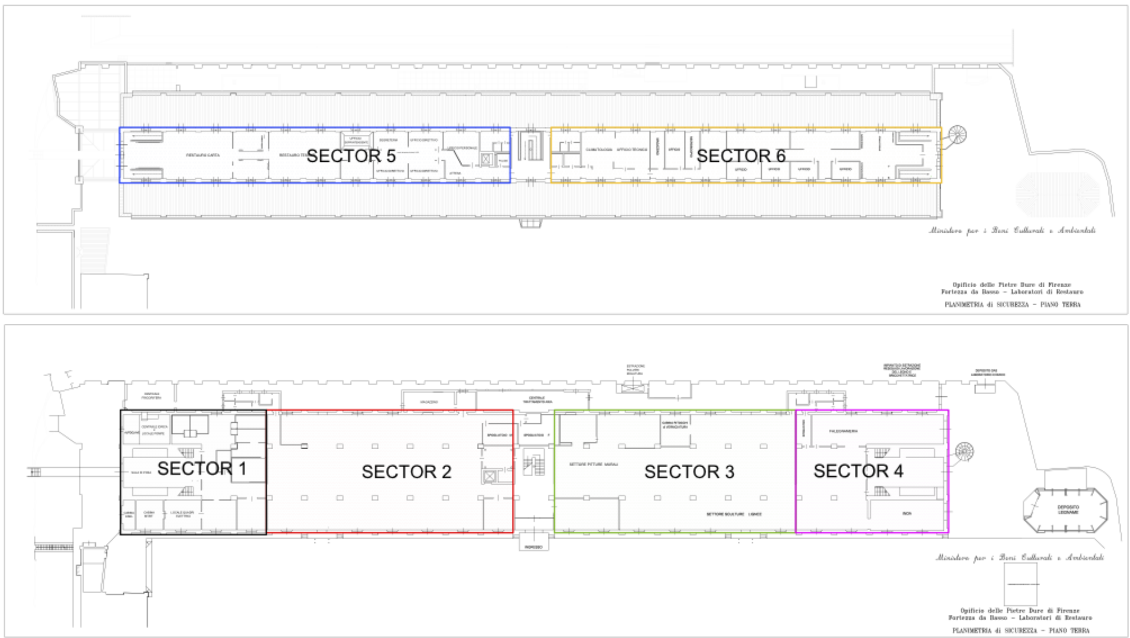


Figure 7.5: Sectors composing OPD Building in Fortezza da Basso, elaboration from [38].

7.1.1 FSI

In OPD building we have a number of FS members greater than 1 for each sector. Every member has "Medium Fire Risk" formation and retraining is done every two years.

$\underline{FSI_1}$
In Table 7.2 risk indexes for IS_i are shown.

Sector	*Number of members in the sector*	IS_i
Sector 1	> 1	0
Sector 2	> 1	0
Sector 3	> 1	0
Sector 4	> 1	0
Sector 5	> 1	0
Sector 6	> 1	0

Table 7.2: Values for IS_i in OPD building.

From the data in Table 7.2 it is possible to calculate

$$FSI = \frac{\sum_{i=1}^{n} IS_i}{n} = 0 \tag{7.1}$$

$\underline{FSI_2}$
In Table 7.3 risk indexes for FSI_2 are shown.

Level of formation	FSI_2
B: medium fire risk	3

Table 7.3: Values for FSI_2 in OPD building.

$\underline{FSI_3}$
In Table 7.4 risk indexes for FSI_3 are shown.

Periodicity	*Type of retrainig* Theoretical and practical
every two years	4

Table 7.4: Values for FSI_3 in OPD building.

From data in tables above FSI according to equation 5.51 assumes the value of 2,3 and, according to Table 5.28, $IF133$ is estimated to be 1,2.

7.1.2 External Characteristics

Table 7.5 shows risk indexes for OPD building in actual situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
EC1	EF 1.1 n° of levels	2 levels, no attic, no underground levels	3,00	3,80	3,60	4,60
	EF 1.2 medium height	H_M minor than 10m	5,00			
EC2	EF 2.1 stairs	missing 1 emergency stair	4,20	4,32	4,48	4,84
	EF2.2 double heights	one of two levels height	5,00			
EC3	EF 3.1 fire brigade response time	10-15 minutes	6,00	6,04	6,04	6,05
	EF3.2 surroundings	3 of the four sides with very good accessibility; 1 side totally not accessible	6,13			
				OB1	OB2	OB3
			RI	4,52	5,00	4,98

Table 7.5: Risk Indexes for External Characteristics in actual situation.

Table 7.6 shows risk indexes for OPD building in best situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
EC1	EF 1.1 n° of levels	2 levels, no attic, no underground levels	3,00	3,80	3,60	4,60
	EF 1.2 medium height	H_M minor than 10m	5,00			
EC2	EF 2.1 stairs	desired number of stairs	0,00	0,75	1,75	4,00
	EF2.2 double heights	one of two levels height	5,00			
EC3	EF 3.1 fire brigade response time	0-5 minutes	2,00	3,44	3,44	3,65
	EF3.2 surroundings	3 of the four sides with very good accessibility; 1 side totally not accessible	6,13			
				OB1	OB2	OB3
			RI	1,99	2,95	4,10

Table 7.6: Risk Indexes for External Characteristics in the best situation.

Figure 7.6 shows relative representation of risk indexes for OPD External Characteristics. The three Risk Indicators for the Objectives are in the "acceptable area".

Since the three points are in the "action area", no compulsory intervention has to be done; in order to be virtuous, building's manager can try to improve the Risk Index for $OB1 - Evacuation$ since it has the lowest LMM. Referring to the mitigation path for OB1 with respect to the External Characteristics, represented in Figure 6.1, mitigation measures have to be taken about Factor $EF2.1 - stairs$. To improve LMM was chosen to built the emergency staircase now missing in the building.

In Table 7.7 risk indexes after OB1 mitigation are reported and in Figure 7.7 results after mitigation are shown. Table 7.8 shows data upon whom to build Figure 7.7.

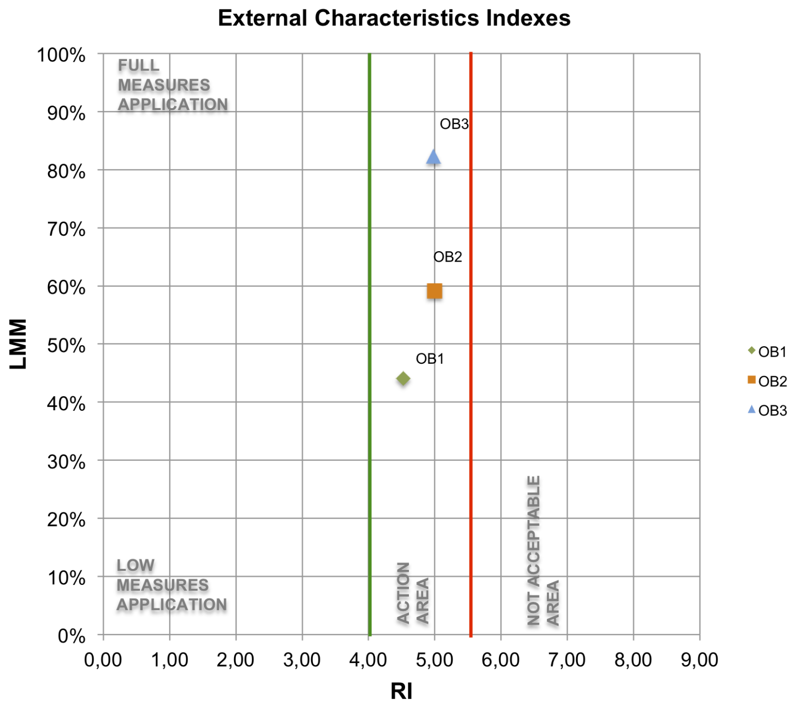


Figure 7.6: Relative representation of the risk indexes for the External Characteristics in OPD building.

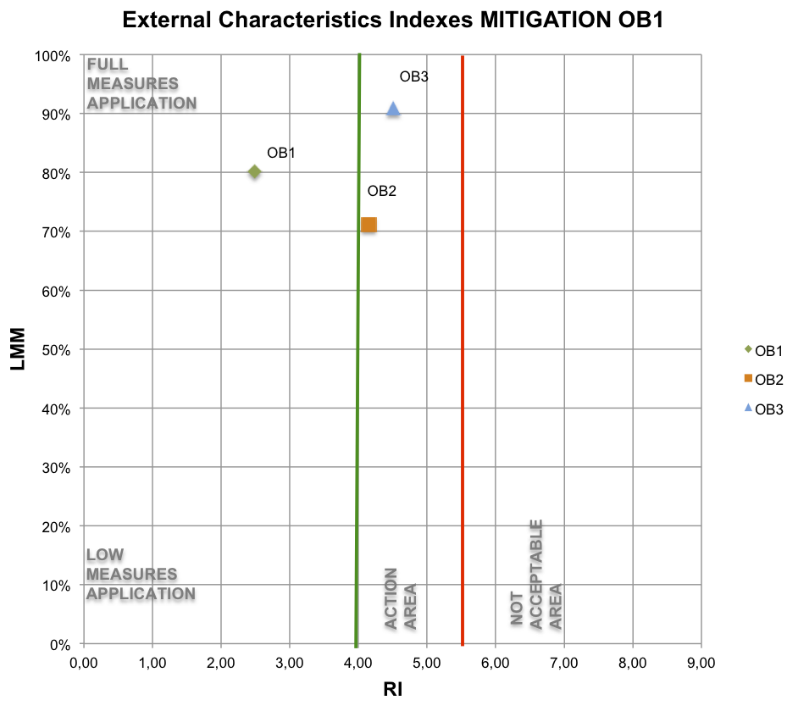


Figure 7.7: Relative representation of the risk indexes for the External Characteristics in OPD building after mitigation of OB1.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
EC1	EF 1.1 n° of levels	2 levels, no attic, no underground levels	3,00	3,80	3,60	4,60
	EF 1.2 medium height	H_M minor than 10m	5,00			
EC2	EF 2.1 stairs	**desired number of emergency stairs**	0,00	0,75	1,75	4,00
	EF2.2 double heights	one of two levels height	5,00			
EC3	EF 3.1 fire brigade response time	10-15 minutes	6,00	6,04	6,04	6,05
	EF3.2 surroundings	3 of the four sides with very good accessibility; 1 side totally not accessible	6,13			
				OB1	OB2	OB3
			RI	2,49	4,15	4,41

Table 7.7: Risk Indexes for External Characteristics after OB1 mitigation.

		Actual situation		*After OB1 mitigation*			
	BI	RI	LMM	RI	LMM	ΔRI	ΔLMM
OB1	1,99	4,52	44%	2,49	80%	2,03	36%
OB2	2,95	5,00	59%	4,15	71%	0,85	12%
OB3	4,10	4,98	82%	4,51	91%	0,47	9%

Table 7.8: Data for relative representation of risk for External Carachteristics after OB1 mitigation in OPD building.

From the above data it is possible to notice how the direct action on the $EF2.1 - stairs$ factor creates a strong reduction of the RI for that Objective and a significant increase of the corresponding LMM. At the same time there are also good secondary effects on the other two Objectives, both in terms of RI and LMM.

7.1.3 Sector 1

Sector 1 is located at the ground floor of the building and it contains storage rooms and the photography laboratory. This sector corresponds with a fire compartment. Table 7.9 shows risk indexes for Sector 1 of OPD building in actual situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	no smoke control system	7,00	4,58	4,66	5,06
	IF 1.2 detection system	at least one wired smoke detector in every room	4,00			
	IF 1.3 suppression system	gas system in rooms with valuable contents and portable extinguish eq. not in every room	4,24			
	IF 1.4 alarm system	alarm bell with signal sent manually to all building	3,40			
IC2	IF 2.1 type of evacuation route	evacuation route used for“first priority” Works of Art	4,05	3,11	3,03	2,41
	IF 2.2 dimensions and layout	max. travel distance between 15 and 30m; less than 2levels; protected stairs	2,00			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	3,96	4,59	4,99

Table 7.9: Risk Indexes for Sector 1 of OPD building in actual situation.

Table 7.10 shows risk indexes for Sector 1 of OPD building in best situation. Figure 7.8 shows relative representation of risk indexes for OPD Sector 1. The three Risk Indicators for the Objectives are in the “acceptable area”.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	performant smoke control system	2,00	1,85	1,89	1,97
	IF 1.2 detection system	Laser detection System or Air sampling detection system everywhere	1,00			
	IF 1.3 suppression system	bet FSI, audit for maintenance, gas system in rooms with valuable contents and portable extinguish eq. not in every room	2,37			
	IF 1.4 alarm system	spoken signal sent manually to all building	2,20			
IC2	IF 2.1 type of evacuation route	evacuation route used for"first priority" Works of Art	4,05	3,11	3,03	2,41
	IF 2.2 dimensions and layout	max. travel distance between 15 and 30m; less than 2levels; not protected stairs	2,00			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	3,27	3,54	3,44

Table 7.10: Risk Indexes for Sector 1 of OPD building in best situation.

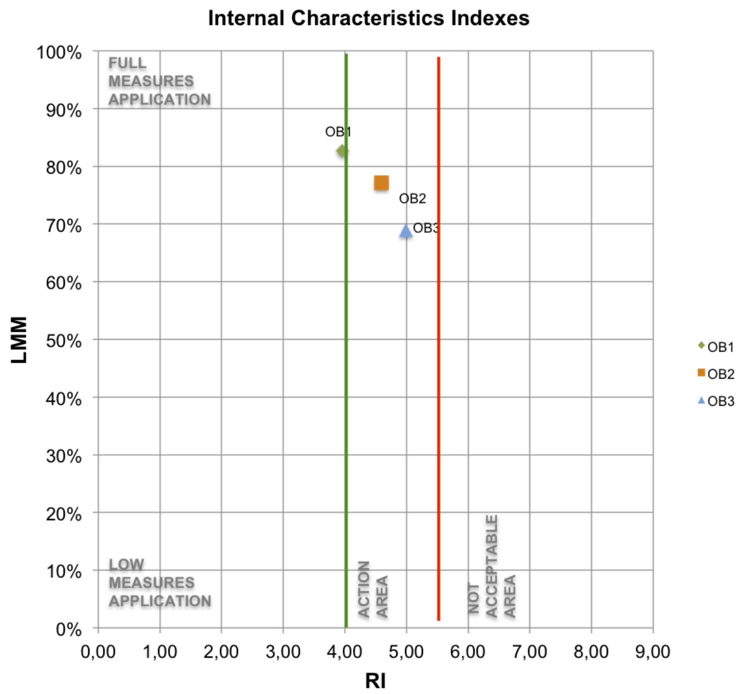


Figure 7.8: Relative representation of the risk indexes for Sector 1 in OPD building.

7.1.4 Sector 2

Sector 2 is located at the ground floor of the building and it contains the Easel painting department. This sector corresponds with a fire compartment. Table 7.11 shows risk indexes for Sector 2 of OPD building in actual situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	no smoke control system	7,00	4,16	4,29	4,79
	IF 1.2 detection system	more than one wired smoke detector in every room	2,50			
	IF 1.3 suppression system	gas system in rooms with valuable contents and portable extinguish eq. not in every room	4,24			
	IF 1.4 alarm system	alarm bell with signal sent manually to all building	3,40			
IC2	IF 2.1 type of evacuation route	evacuation route used for“first priority” Works of Art	4,05	3,11	3,03	2,41
	IF 2.2 dimensions and layout	max. travel distance between 15 and 30m; less than 2levels; protected stairs	2,00			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	3,85	4,45	4,85

Table 7.11: Risk Indexes for Sector 2 of OPD building in actual situation.

Table 7.12 shows risk indexes for Sector 2 of OPD building in best situation.

Figure 7.9 shows relative representation of risk indexes for OPD Sector 1. The three Risk Indicators for the Objectives are in the “acceptable area”.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	performant smoke control system	2,00	1,85	1,89	1,97
	IF 1.2 detection system	Laser detection System or Air sampling detection system everywhere	1,00			
	IF 1.3 suppression system	bet FSI, audit for maintenance, gas system in rooms with valuable contents and portable extinguish eq. not in every room	2,37			
	IF 1.4 alarm system	spoken signal sent manually to all building	2,20			
IC2	IF 2.1 type of evacuation route	evacuation route used for"first priority" Works of Art	4,05	2,81	2,74	2,01
	IF 2.2 dimensions and layout	max. travel distance between 15 and 30m; less than 2levels; protected stairs	1,00			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	3,11	3,45	3,37

Table 7.12: Risk Indexes for Sector 2 of OPD building in best situation.

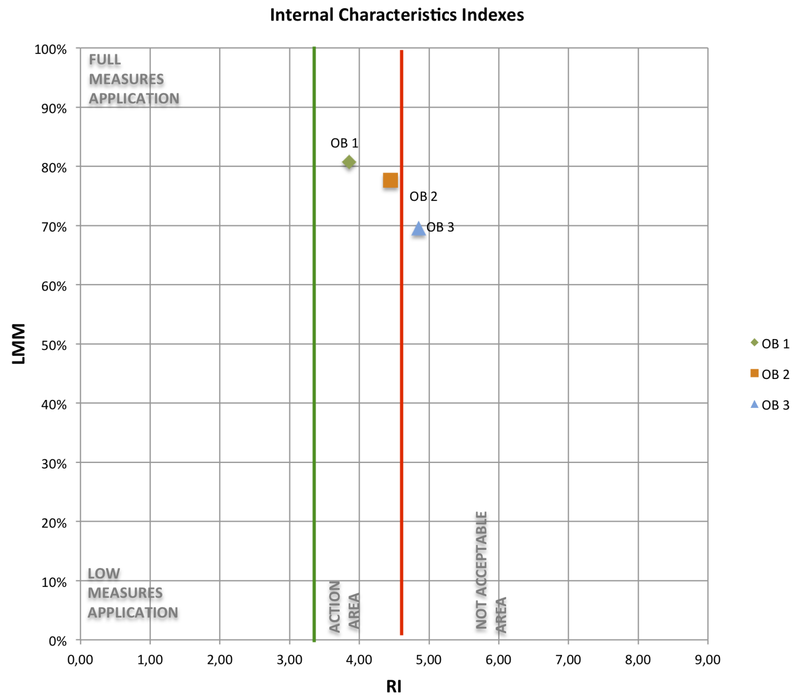


Figure 7.9: Relative representation of the risk indexes for Sector 2 in OPD building.

7.1.5 Sector 3

Sector 3 is located at the ground floor of the building and contains the Wooden Sculptures and Wall Painting departments. This sector corresponds with a fire compartment. Table 7.13 shows risk indexes for Sector 3 of OPD building in actual situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	no smoke control system	7,00	4,19	4,33	4,85
	IF 1.2 detection system	more than one wired smoke detector in every room	2,50			
	IF 1.3 suppression system	gas system in rooms with valuable contents and portable extinguish eq. not in every room	4,40			
	IF 1.4 alarm system	alarm bell with signal sent manually to all building	3,40			
IC2	IF 2.1 type of evacuation route	evacuation route used for"first priority" Works of Art	4,05	2,81	2,74	2,01
	IF 2.2 dimensions and layout	max. travel distance between 15 and 30m; less than 2 levels; protected stairs	1,00			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	3,70	4,38	4,81

Table 7.13: Risk Indexes for Sector 3 of OPD building in actual situation.

Table 7.14 shows risk indexes for Sector 3 of OPD building in best situation.

Figure 7.10 shows relative representation of risk indexes for OPD Sector 1. The three Risk Indicators for the Objectives are in the "acceptable area".

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	performant smoke control system	2,00	1,88	1,94	2,04
	IF 1.2 detection system	Laser detection System or Air sampling detection system everywhere	1,00			
	IF 1.3 suppression system	bet FSI, audit for maintenance, gas system in rooms with valuable contents and portable extinguish eq. not in every room	2,56			
	IF 1.4 alarm system	spoken signal sent manually to all building	2,20			
IC2	IF 2.1 type of evacuation route	evacuation route used for "first priority" Works of Art	4,05	2,81	2,74	2,01
	IF 2.2 dimensions and layout	max. travel distance between 15 and 30m; less than 2levels; protected stairs	1,00			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	3,12	3,47	3,41

Table 7.14: Risk Indexes for Sector 3 of OPD building in best situation.

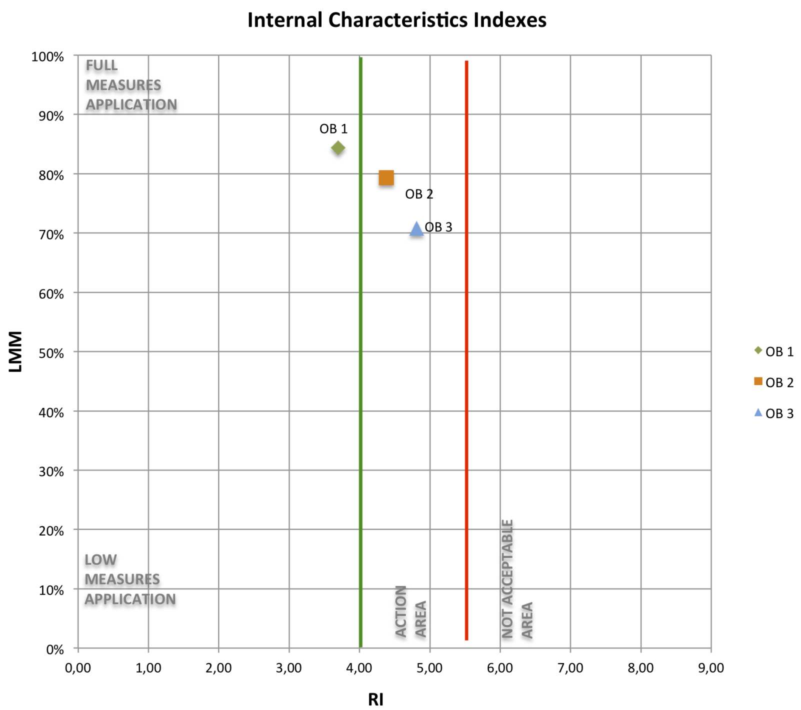


Figure 7.10: Relative representation of the risk indexes for Sector 3 in OPD building.

7.1.6 Sector 4

Sector 4 is located at the ground floor of the building and it contains carpentry and laboratories. This sector is a fire compartment. Table 7.15 shows risk indexes for Sector 4 of OPD building in actual situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	no smoke control system	7,00	4,24	4,39	4,93
	IF 1.2 detection system	at least one wired smoke detector in every room	2,50			
	IF 1.3 suppression system	gas system in rooms with valuable contents and portable extinguish eq. not in every room	4,64			
	IF 1.4 alarm system	alarm bell with signal sent manually to all building	3,40			
IC2	IF 2.1 type of evacuation route	evacuation route used for"first priority" Works of Art	4,05	3,11	3,03	2,41
	IF 2.2 dimensions and layout	max. travel distance between 15 and 30m; less than 2 levels; not protected stairs	2,00			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	3,87	4,49	4,92

Table 7.15: Risk Indexes for Sector 4 of OPD building in actual situation.

Table 7.16 shows risk indexes for Sector 4 of OPD building in best situation.

Figure 7.11 shows relative representation of risk indexes for OPD Sector 4. The three Risk Indicators for the Objectives are in the "acceptable area".

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	performant smoke control system	2,00	1,85	1,89	1,97
	IF 1.2 detection system	Laser detection System or Air sampling detection system everywhere	1,00			
	IF 1.3 suppression system	best FSI, audit for maintenance, gas system in rooms with valuable contents and portable extinguish eq. not in every room	2,37			
	IF 1.4 alarm system	spoken signal sent manually to all building	2,20			
IC2	IF 2.1 type of evacuation route	evacuation route used for"first priority" Works of Art	4,05	3,11	3,03	2,41
	IF 2.2 dimensions and layout	max. travel distance between 15 and 30m; less than 2levels; not protected stairs	2,00			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	3,27	3,54	3,44

Table 7.16: Risk Indexes for Sector 4 of OPD building in best situation.

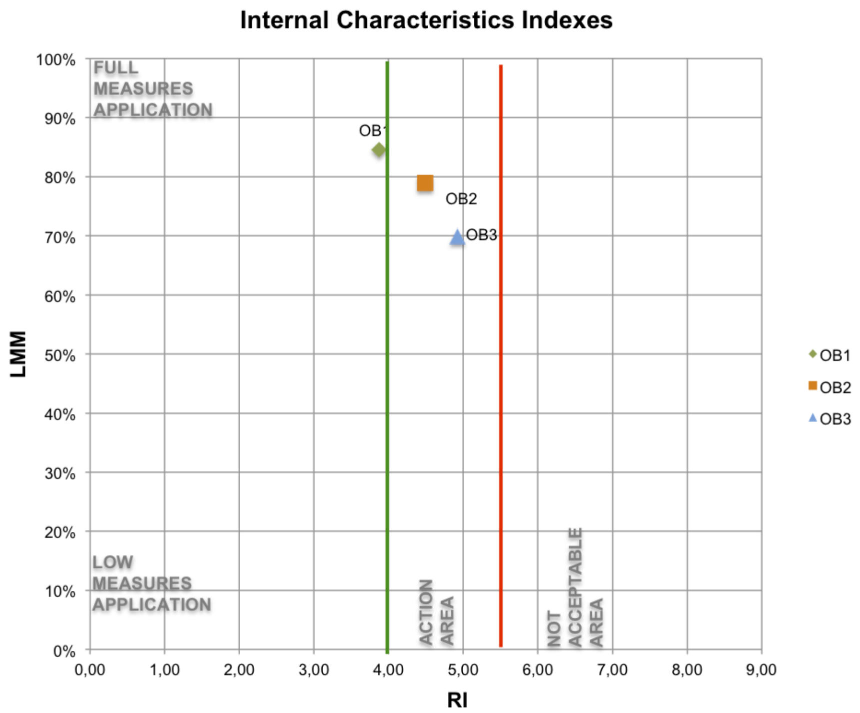


Figure 7.11: Relative representation of the risk indexes for Sector 4 in OPD building.

7.1.7 Sector 5

Sector 5 is located at the first floor of the building and it contains Textile department and offices. In this side of the building a staircase is missing with respect to the desired number of egress safe stairs. Table 7.17 shows risk indexes for Sector 5 of OPD building in actual situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	no smoke control system	7,00	5,10	5,18	5,53
	IF 1.2 detection system	at least one wired smoke detector in every room	5,5			
	IF 1.3 suppression system	no automatic system in the whole sector	4,80			
	IF 1.4 alarm system	alarm bell with signal sent manually to all building	3,40			
IC2	IF 2.1 type of evacuation route	evacuation route used for“first priority” Works of Art and direct escpae to two escape routes	6,45	4,10	3,94	2,49
	IF 2.2 dimensions and layout	max. travel distance between 15 and 30m; less than 2 levels; protected stairs	1,00			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	4,63	5,06	5,23

Table 7.17: Risk Indexes for Sector 5 of OPD building in actual situation.

Table 7.18 shows risk indexes for Sector 5 of OPD building in best situation.

Figure 7.12 shows relative representation of risk indexes for OPD Sector 5. The three Risk Indicators for the Objectives are in the “acceptable area”.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	performant smoke control system	2,00	1,88	1,94	2,04
	IF 1.2 detection system	Laser detection System or Air sampling detection system everywhere	1,00			
	IF 1.3 suppression system	best FSI, audit for maintenance, gas system in rooms with valuable contents and portable extinguish eq. not in every room	2,56			
	IF 1.4 alarm system	spoken signal sent manually to all building	2,20			
IC2	IF 2.1 type of evacuation route	evacuation route used for"first priority" Works of Art and direct escape to two escape routes	6,45	4,10	3,94	2,49
	IF 2.2 dimensions and layout	max. travel distance between 15 and 30m; less than 2 levels; protected stairs	1,00			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	3,82	3,83	3,49

Table 7.18: Risk Indexes for Sector 5 of OPD building in best situation.

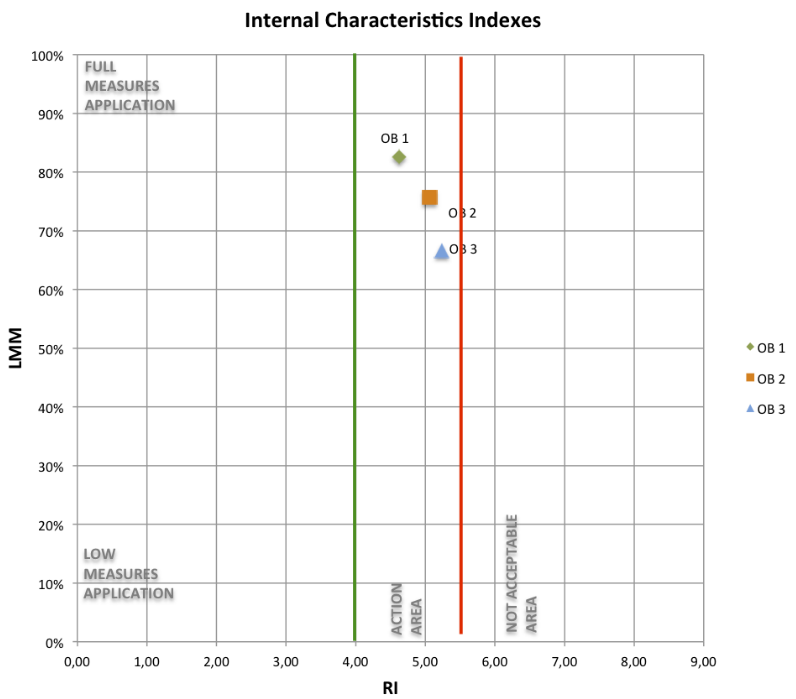


Figure 7.12: Relative representation of the risk indexes for Sector 5 in OPD building.

7.1.8 Sector 6

Sector 6 is located at the first floor of the building and contains laboratories and offices. Table 7.19 shows risk indexes for Sector 6 of OPD building in actual situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	no smoke control system	7,00	5,10	5,18	5,53
	IF 1.2 detection system	at least one wired smoke detector in every room	5,5			
	IF 1.3 suppression system	no automatic system in the whole sector	4,80			
	IF 1.4 alarm system	alarm bell with signal sent manually to all building	3,40			
IC2	IF 2.1 type of evacuation route	evacuation route used for“first priority” Works of Art and direct escape to two escape routes	6,45	4,10	3,94	2,49
	IF 2.2 dimensions and layout	max. travel distance between 15 and 30m; less than 2 levels; protected stairs	1,00			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	4,63	5,06	5,23

Table 7.19: Risk Indexes for Sector 6 of OPD building in actual situation.

Table 7.20 shows risk indexes for Sector 6 of OPD building in best situation.

Figure 7.13 shows relative representation of risk indexes for OPD Sector 6. The three Risk Indicators for the Objectives are in the “acceptable area”.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	performant smoke control system	2,00	1,88	1,94	2,04
	IF 1.2 detection system	Laser detection System or Air sampling detection system everywhere	1,00			
	IF 1.3 suppression system	best FSI, audit for maintenance, gas system in rooms with valuable contents and portable extinguish eq. not in every room	2,56			
	IF 1.4 alarm system	spoken signal sent manually to all building	2,20			
IC2	IF 2.1 type of evacuation route	evacuation route used for"first priority" Works of Art and direct escape to two escape routes	6,45	4,10	3,94	2,49
	IF 2.2 dimensions and layout	max. travel distance between 15 and 30m; less than 2 levels; protected stairs	1,00			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	3,82	3,83	3,49

Table 7.20: Risk Indexes for Sector 6 of OPD building in best situation.

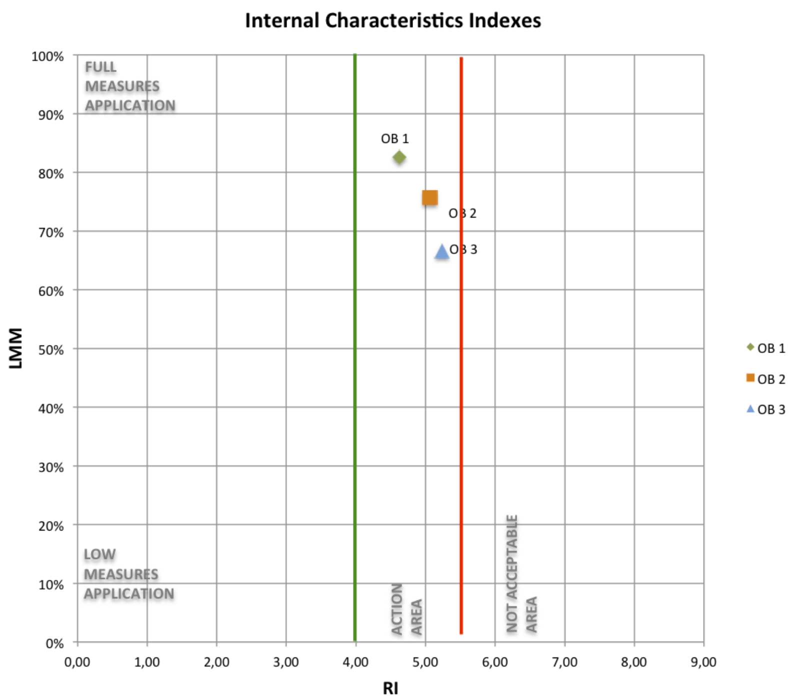


Figure 7.13: Relative representation of the risk indexes for Sector 6 in OPD building.

7.1.9 Remarks on OPD case study

The Opificio delle Pietre Dure building in Fortezza da Basso has a very simple architectonical configuration and distribution. Despite this profitable aspect, we have inside the building some of the most important works of art in Art History.

From the above data it is possible to notice that all the Risk Indicators are inside the "action area", so they are acceptable with respect to the stated acceptance criteria. None of the Sectors needs mitigation measures, an example of mitigation with respect to the External Characteristics it is just reported in order to give an example of the Risk Treatment Method application. OPD base is an example of building that could have had a smaller "acceptable area" with respect to the acceptance criteria. Most of the Risk Indicators are around 5 and the building's manager could have choose 5 as upper limit (instead of 5,5) to increase more and more the performance required to the building in contents protection.

As said, we chose upper limit of 5,5 to make easier the comparison with the second case study Palazzo Chigi Saracini.

7.2 Palazzo Chigi Saracini

In this section the results deriving from the application of the procedure to an historical building in Siena are presented. The analysed building is “Palazzo Chigi Saracin”, seat of the “Accademia Chigiana” [65]. Palazzo Chigi Saracini was built on a previous building from the thirteenth century Marescotti family who had his castle at that place. It was enlarged in sec. XVI, in the second half of the 700 remodeled and renovated at the beginning of 900. The building still retains the typical aspect of “Senese” Gothic, stones and bricks, with three-light windows, battlements and a tower of stone. These main stages of transformation and growth correspond to the various changes of ownership: each owner has in fact left his “footprint”.

In table 7.21 from Lusini [78] a resume of the main transformation of the building are shown.

Figure 7.14 gives a representation of the building while Figures 7.15 and 7.16 show the building today.

Figure 7.14: A picture of the palace.

Figure 7.15: Entrance of the palace.

Figure 7.16: An interior.

Period	*Facts*
1147	The Marescotti submit to the City of Siena, they occupy the space in an old Roman tower perched at the edge of Galgario way to build their home. Several members of the family then built the house around the common courtyard on which each one had a separate entrance. The Palace was the base, for a long time between thirteenth and fourteenth centuries, of the Council of Rulers of the Republic of Siena, before it was permanently transferred to the building “Palazzo Pubblico”. The most memorable event in the history of the Republic of Siena is related to the ancient Palace Marescotti: the victory against Florence in Monteaperti. The chronicles tell that in that fateful day the drummer Ceccolini Cerreto, from the tower of Marescotti, described the stages of the battle that took place at the Arbia.
Middle XV century	It is buried the lane from East; the level of the Palace courtyard is then raised. The court is closed with a wall built to the east. Finally, to the west is built the portico with two-story lodge on top.
1488	The Marescotti family sell the palace to Piccolomini Mandoli family. These extended or modified the North wing of the palace and then awaited with particular interest in interior decoration especially in the north wing. The ground floor of the lodge had an airy fifteenth grotesque decoration, attributed to Giorgio di Giovanni.
1770	The palace passes to the Saracini family and the façade is extended along the curve of the via di Città.
1787	Galgano Saracini commissions the expansion of the building. The factory covers both downstream and upstream of the original nucleus. Many windows are moved to achieve symmetry and, disregarding the remains of battlements Ghibellines, the battlements are rebuilt Guelphs like those of other buildings in the city.
1806	Thanks to Galgano Saracens the palace is enriched his important collection of works of art, well over twelve thousand pieces. In the same year was inaugurated the museum, housed in the Gothic palace and open to the public of art lovers.
1877	Extinction of the Saracini family. Chigi family inherits the palace.
1914-1925	General renovation of the building taking care, especially, of the external facades of the main courtyard and atrium. Intervenes in the internal stairs to the different distribution plans and reorganization of some of the rooms on the second floor [100].
1932	By the will of Count Guido Chigi, it is established the Music Academy, an international centre for advanced musical studies [95].
Present time	The Chigiana Academy holds in its interior a huge collection of works of art belonging to the greatest artists of Italian painting, especially Siena, including the Sassetta, Sodoma, Beccafumi, Botticelli, and includes many sculptures, ivory objects, porcelain, silver and a collection of ceramics [106]. The Chigiana Academy also has a library both literary and musical, which includes about 70,000 volumes, rich in rare editions, autographs, manuscripts of various periods and a fine collection of musical instruments especially for arco.

Table 7.21: Chronology of the Palazzo Chigi Saracini transformations.

In its present configuration, the building has two underground levels, the ground floor and four floors above ground. At the basement there are some technical areas (sometimes made the recesses of the building) and, above all, some rooms used as storage or archive. On the second basement level there are many locals dug directly into the "tufo" stone, which are largely unused. On the upper floors are the local music school and concert hall. There are also some rooms used as offices, housing for caretakers, the concierge. At the top floor are other rooms used as storage (or could be used for this purpose). Among these, the local "picture gallery" in which there are paintings of great value. Figure 7.17 shows the urban location of the building, Figure 7.18 shows the ground floor plan of the building while Figures 7.19 and 7.19 show two sections.

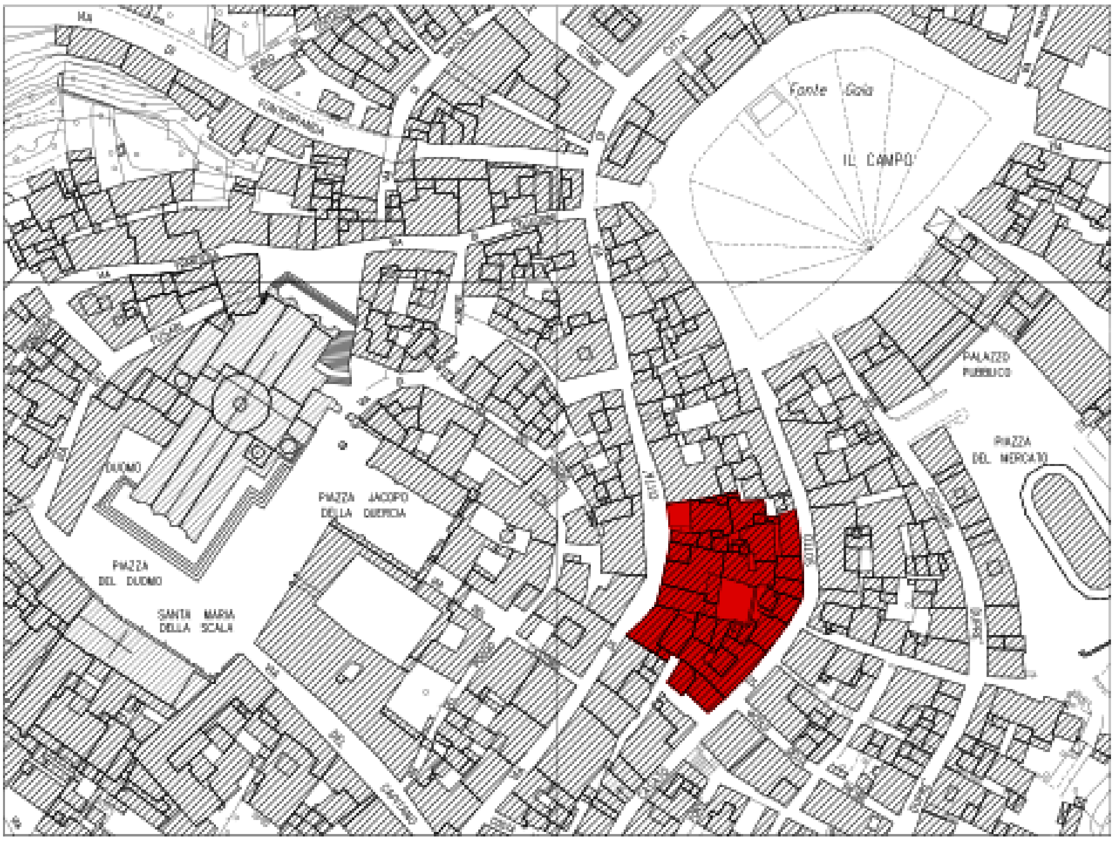


Figure 7.17: The palace in the city plan.

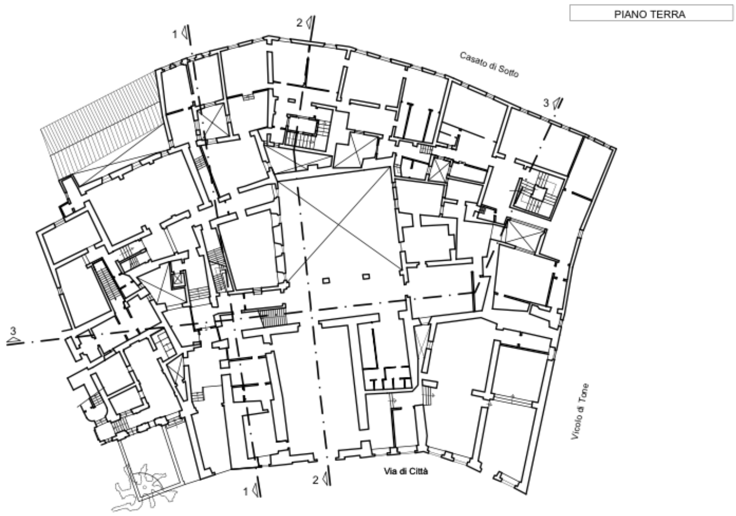


Figure 7.18: Ground floor plan.

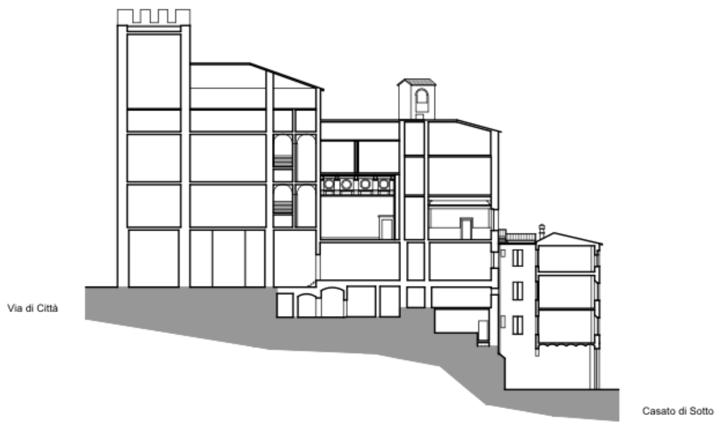


Figure 7.19: Section 1-1.

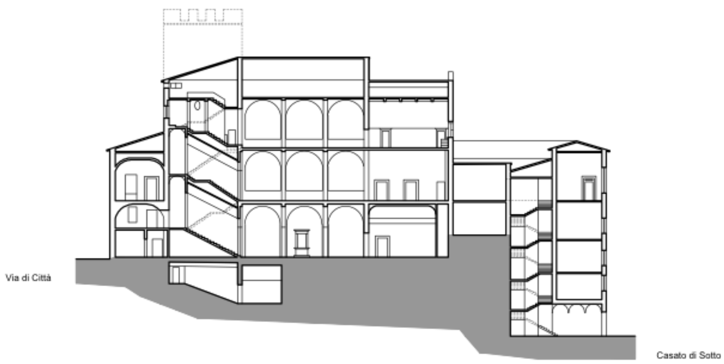


Figure 7.20: Section 3-3.

Activity	*Place*	*Period*	*n° of persons*
Offices	First and second floor	All year long	15 persons
Concierge	Mezzanine floor	All year long	2 persons
Music School	Ground and first floor	Only in July and August	less than 100 persons
Concerts	Concert hall at first and second floor	15 days in a year	maximum 260 persons
Temporary exhibitions	Ground floor	-	-
Museum	First floor	From April to October, 4 visits 1hour long per day	-
Library	Second Floor	All year long	maximum 5 persons
Archives	Underground floors and third floor	-	-

Table 7.22: Synthesis of the different destination of use of Palazzo Chigi Saracini.

In Palazzo Chigi Saracini there are a lot of different activities. In table 7.22 a resume of the destination of use of the different areas of the building is reported. Sectors considered in the Internal Characteristics analysis are:

- Sector 1: library;
- Sector 2: storage rooms;
- Sector 3: musical instruments museum;
- Sector 4: main museum;
- Sector 5: quadreria;
- Sector 6: theatre.

In the procedure's application, only parts of the building containing works of art are interesting. This is the reason why offices are not considered as a sector. All the others considered sectors contain valuable contents; a music school is set up in the summer in the rooms of the main museum. Some sectors overlap each other; theatre's stalls i.e. is a part of the main museum path and it is considered both in the "sector 4:main museum" and in the "sector 6: theatre".

7.2.1 FSI

In Palazzo Chigi Saracini we have only one FS member for each sector. Every member has "Medium Fire Risk" formation and retraining is done every two years.

$\underline{FSI_1}$

In Table 7.23 risk indexes for IS_i are shown.

Sector	*Number of members in the sector*	IS_i
Sector 1	1	3
Sector 2	1	3
Sector 3	1	3
Sector 4	1	3
Sector 5	1	3
Sector 6	> 1	0

Table 7.23: Values for IS_i in Palazzo Chigi Saracini.

From the data in Table 7.23 it is possible to calculate

$$FSI = \frac{\sum_{i=1}^{n} IS_i}{n} = 2,5 \tag{7.2}$$

$\underline{FSI_2}$

In Table 7.24 risk indexes for FSI_2 are shown.

Level of formation	FSI_2
B: medium fire risk	3

Table 7.24: Values for FSI_2 in Palazzo Chigi Saracini.

$\underline{FSI_3}$

In Table 7.25 risk indexes for FSI_3 are shown.

Periodicity	*Type of retrainig* Theoretical and practical
every two years	4

Table 7.25: Values for FSI_3 in Palazzo Chigi Saracini.

From data in tables above FSI according to equation 5.51 assumes the value of 3,2 and, according to Table 5.28, $IF133$ is estimated to be 1,5.

7.2.2 External Characteristics

Since the building shows such architectonical complexity, Medium Height is considered to be the one corresponding to the height of the main facade in via di città. Tower was not considered so $H_M < 22m$. Table 7.26 shows risk indexes for Palazzo Chigi Saracini in actual situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
EC1	EF 1.1 n° of levels	4 levels, attic, 2 underground levels	10,56	9,14	9,49	7,71
	EF 1.2 medium height	H_M minor than 22m	7,00			
EC2	EF 2.1 stairs	number of desired stairs egual to the existent stairs	0,00	0,75	1,75	5,20
	EF2.2 double heights	one of two levels height, possible presence of ancient flues and chimneys	5,00			
EC3	EF 3.1 fire brigade response time	5-10 minutes	4,00	4,68	4,68	4,78
	EF3.2 surroundings	in historical centre with traffic restrictions, 2 sides with good accessibility, streets quite large	5,95			
				OB1	OB2	OB3
			RI	3,51	4,88	5,81

Table 7.26: Risk Indexes for External Characteristics in Palazzo Chigi Saracini actual situation.

Table 7.27 shows risk indexes for Palazzo Chigi Saracini in best situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
EC1	EF 1.1 n° of levels	4 levels, attic, 2 underground levels	10,56	9,14	9,49	7,71
	EF 1.2 medium height	H_M minor than 22m	7,00			
EC2	EF 2.1 stairs	number of desired stairs equal to the existent stairs	0,00	0,75	1,75	4,00
	EF2.2 double heights	one of two levels height, ancient flues and chimneys are sealed	4,00			
EC3	EF 3.1 fire brigade response time	reduced to 0-5 minutes	2,00	3,38	3,38	3,58
	EF3.2 surroundings	in historical centre with traffic restrictions, 2 sides with good accessibility, streets quite large	5,95			
				OB1	OB2	OB3
			RI	3,26	4,28	4,93

Table 7.27: Risk Indexes for External Characteristics in Palazzo Chigi Saracini best situation.

Figure 7.21 shows relative representation of risk indexes for Palazzo Chigi Saracini External Characteristics. Two of the three Risk Indicators for the Objectives are in the "acceptable area" while OB3 is in the "not acceptable" area.

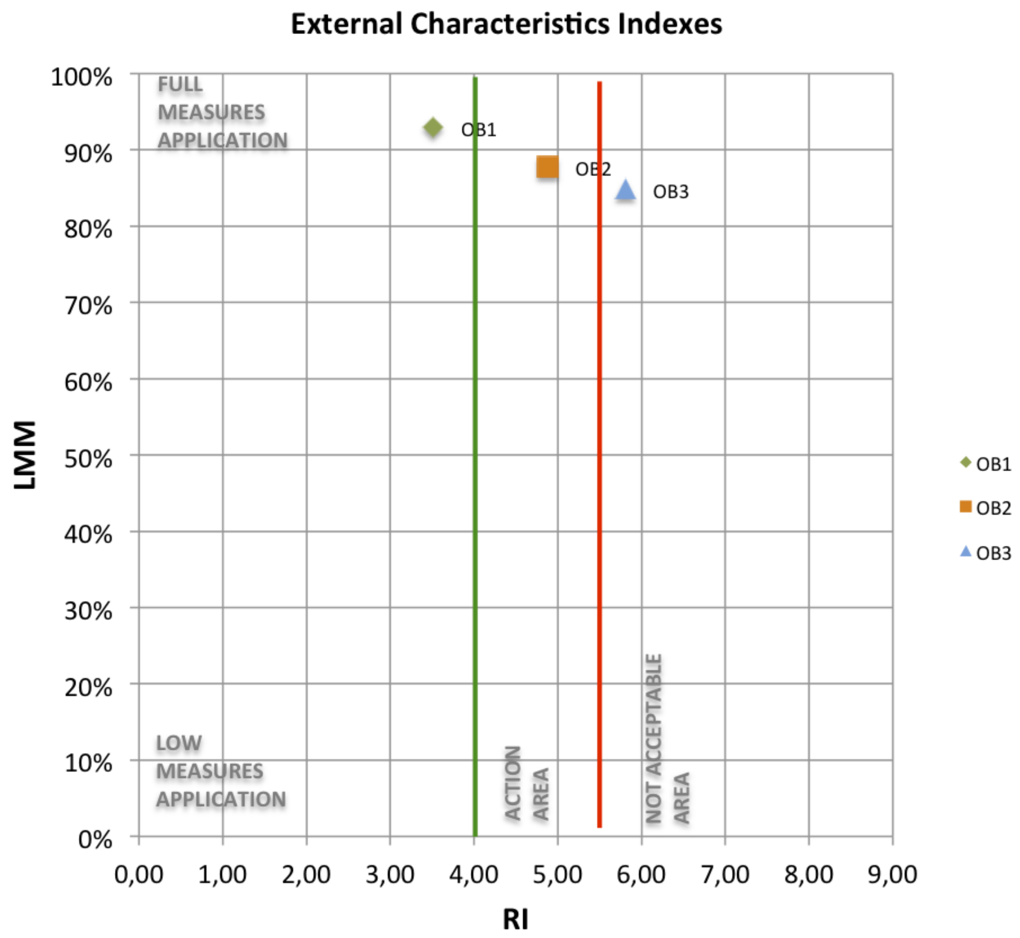


Figure 7.21: Relative representation of the risk indexes for the External Characteristics in Palazzo Chigi Saracini.

According to the procedure, an intervention has to be done in order to improve the Risk Index for $OB3 - Fire\ and\ smoke\ spread$. Referring to the mitigation path for OB3 with respect to the External Characteristics, represented in Figure 6.3, mitigation measures have to be taken about Factor $EF2.2-double\ heights$. The specific measure here proposed is to close all the flues and chimneys in order to reduce the vertical connections among floors.

In Table 7.28 risk indexes after OB3 mitigation are reported and in Figure 7.22 results after mitigation are shown. Table 7.29 shows data upon whom to build Figure 7.22.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
EC1	EF 1.1 n° of levels	4 levels, attic, 2 underground levels	10,56	9,14	9,49	7,71
	EF 1.2 medium height	H_M minor than 22m	7,00			
EC2	EF 2.1 stairs	number of desired stairs equal to the existent stairs	0,00	0,75	1,75	4,00
	EF2.2 double heights	one of two levels height, **ancient flues and chimneys are sealed**	4,00			
EC3	EF 3.1 fire brigade response time	5-10 minutes	4,00	4,68	4,68	4,78
	EF3.2 surroundings	in historical centre with traffic restrictions, 2 sides with good accessibility, streets quite large	5,95			
				OB1	OB2	OB3
			RI	3,51	4,88	5,13

Table 7.28: Risk Indexes for External Characteristics after OB3 mitigation in Palazzo Chigi Saracini.

		Actual situation		*After OB1 mitigation*			
	BI	*RI*	*LMM*	*RI*	*LMM*	ΔRI	ΔLMM
OB1	3,26	3,51	93%	3,51	93%	0,00	0%
OB2	4,28	4,88	88%	4,88	88%	0,00	0%
OB3	4,93	5,81	85%	5,13	96%	0,67	11%

Table 7.29: Data for relative representation of risk for External Characteristics after OB3 mitigation in Palazzo Chigi Saracini.

From the above data it is possible to notice how the direct action on the $EF2.2 -$ *double heights* factor create a reduction of the RI only for the considered Objective and a significant increase of the corresponding LMM. No secondary effect on the other Objectives is detected.

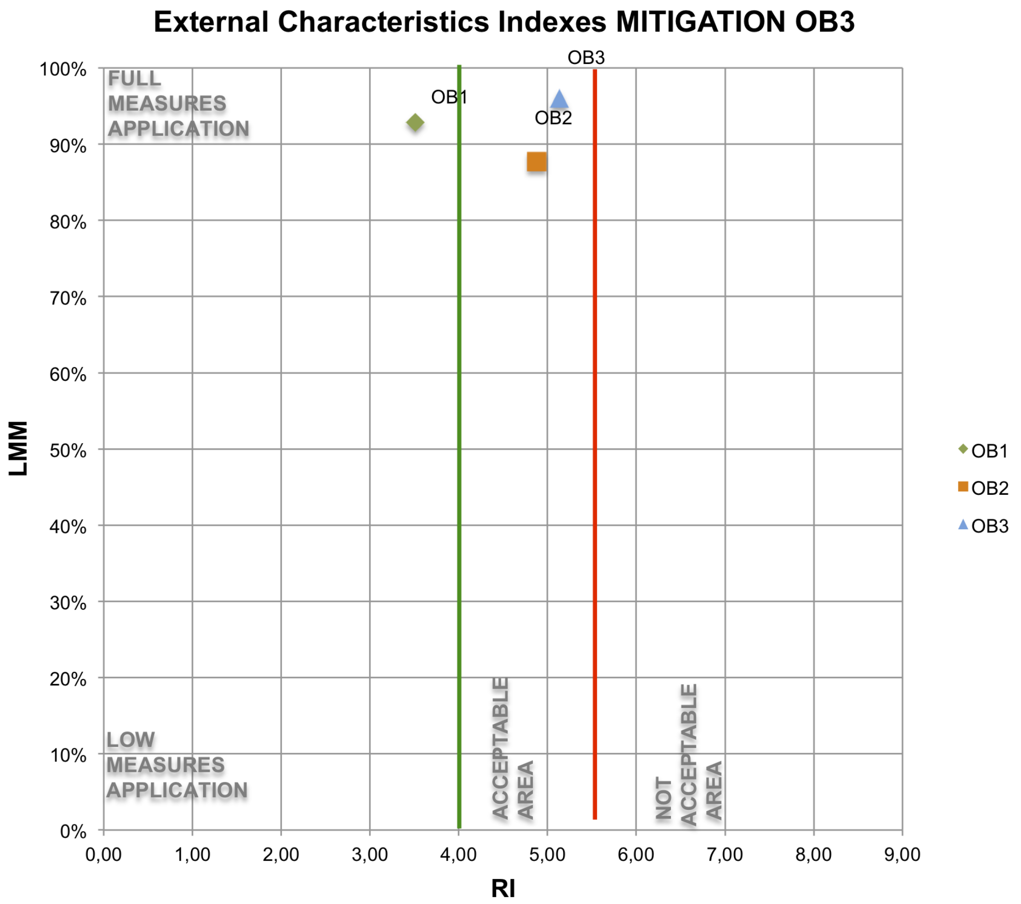


Figure 7.22: Relative representation of the risk indexes for the External Characteristics in Palazzo Chigi Saracini after mitigation of OB3.

7.2.3 Sector 1: library

The historic library of Palazzo Chigi Saracini, containing ancient manuscripts and books, is located at second floor of the building. Figure 7.23 shows sector 1 in the building plan.

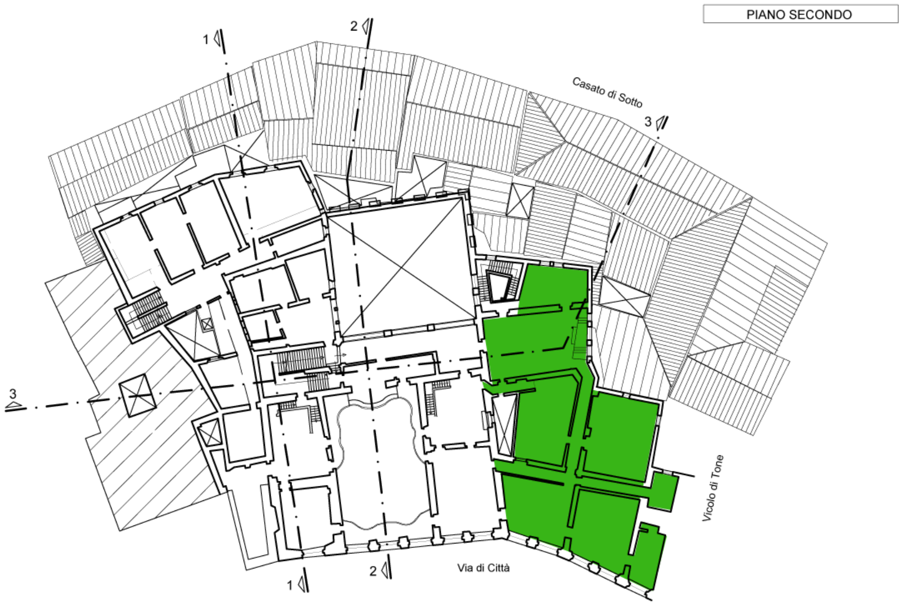


Figure 7.23: Sector 1 identification.

Table 7.30 shows risk indexes for Sector 1 of Palazzo Chigi Saracini in actual situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	no smoke control system	7,00	6,75	6,88	7,18
	IF 1.2 detection system	no detection system	9,0			
	IF 1.3 suppression system	no automatic system and portable extinguish eq. not in every room, Fire service at law minimum compliance	7,50			
	IF 1.4 alarm system	alarm bell in the sector	4,00			
IC2	IF 2.1 type of evacuation route	evacuation route used for “third priority” Works of Art and direct escape to two escape routes	5,50	4,94	4,77	4,10
	IF 2.2 dimensions and layout	max. travel distance >30m; 3 levels to walk; not protected stairs	5,50			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	3,00	3,00	3,00
	IF3.2 horizontal structure	stone, bricks	3,00			
				OB1	OB2	OB3
			RI	4,98	5,03	5,27

Table 7.30: Risk Indexes for Sector 1 of Palazzo Chigi Saracini in actual situation.

Table 7.31 shows risk indexes for Sector 1 of Palazzo Chigi Saracini in best situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	performant smoke control system	2,00	1,58	1,78	1,77
	IF 1.2 detection system	Laser detection System or Air sampling detection system everywhere	1,0			
	IF 1.3 suppression system	best FSI, audit for maintenance, gas system in rooms with valuable contents and portable extinguish in every room	2,37			
	IF 1.4 alarm system	spoken signal sent manually to all building	2,20			
IC2	IF 2.1 type of evacuation route	evacuation route used for “third priority” Works of Art and direct escape to two escape routes	5,50	4,94	4,77	4,10
	IF 2.2 dimensions and layout	max. travel distance >30m; 3 levels to walk; not protected stairs	5,50			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	3,00	3,00	3,00
	IF3.2 horizontal structure	stone, bricks	3,00			
				OB1	OB2	OB3
			RI	3,69	3,10	2,57

Table 7.31: Risk Indexes for Sector 1 of Palazzo Chigi Saracini in best situation.

Figure 7.24 shows relative representation of risk indexes for Palazzo Chigi Saracini Sector 1. The three Risk Indicators for the Objectives are in the “acceptable area”.

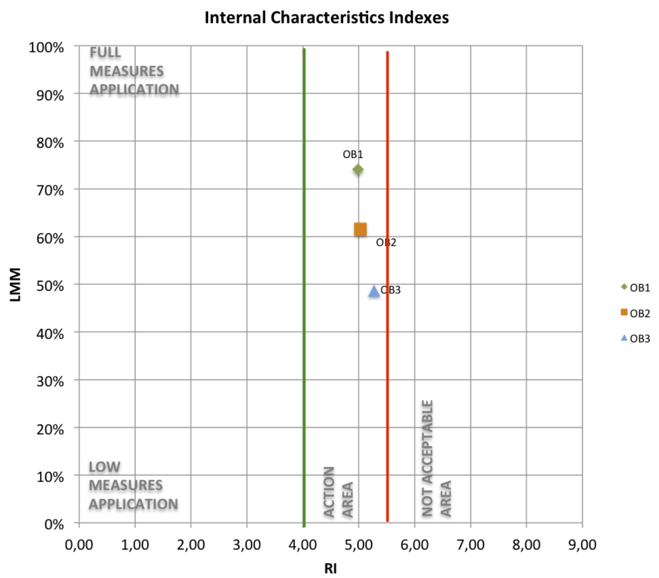


Figure 7.24: Relative representation of the risk indexes for Palazzo Chigi Saracini Sector 1.

7.2.4 Sector 2: storage rooms

Storage rooms are one of the most tricky weak point in historical buildings in case of fire. Usually a large amount of precious contents is put inside them but their location in the building is often critical with respect to the evacuation and fire and smoke spread. In Palazzo Chigi Saracini storage rooms are located at the underground floor and at the ground floor. Because of their disadvantageous location, just underground storage rooms are here analysed.

Figures 7.25 and 7.26 show the location of storage rooms in the building plan.

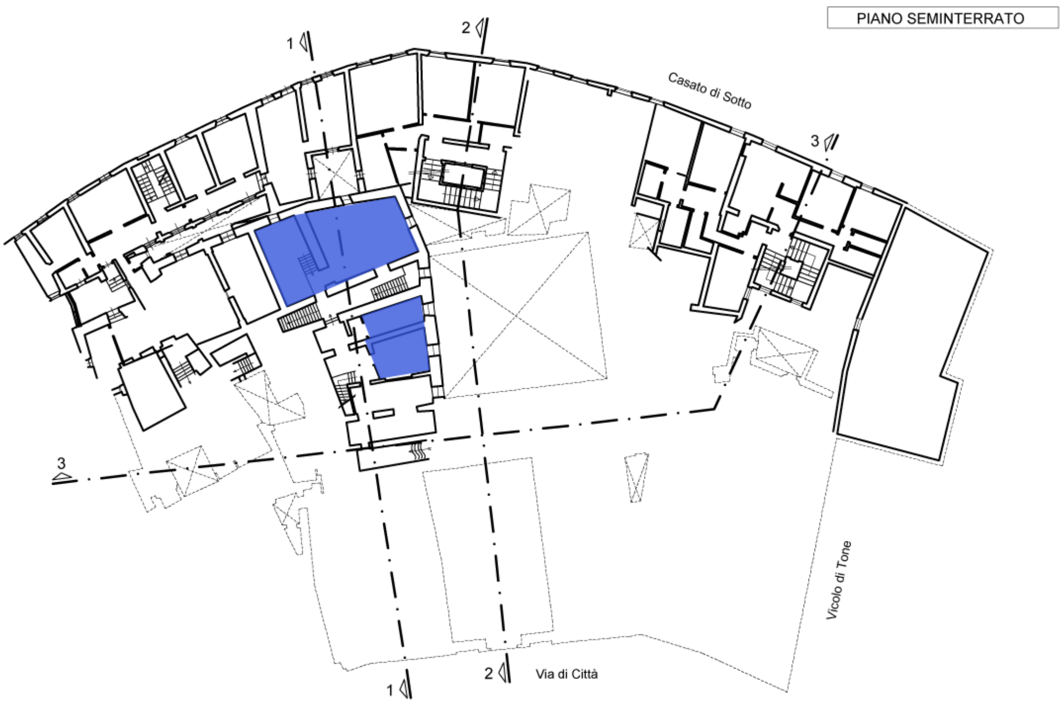


Figure 7.25: Storage rooms in underground floor.

Table 7.32 shows risk indexes for Sector 2 of Palazzo Chigi Saracini in actual situation.

Table 7.33 shows risk indexes for Sector 2 of Palazzo Chigi Saracini in best situation. Figure 7.27 shows relative representation of risk indexes for Palazzo Chigi Saracini Sector 2. No one of the three Risk Indicators for the Objectives is in the "acceptable area".

Figure 7.26: Storage rooms in ground floor.

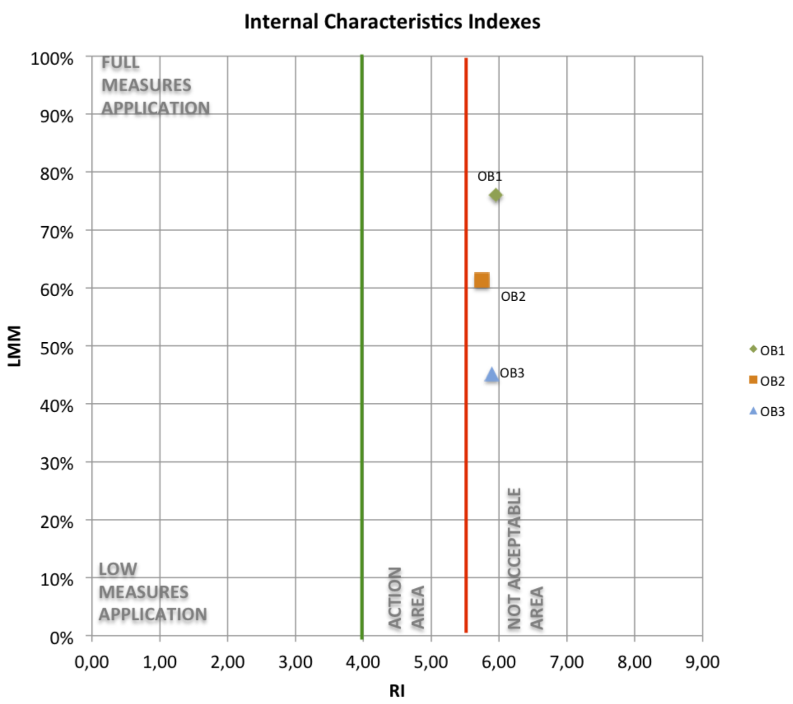


Figure 7.27: Relative representation of the risk indexes for Palazzo Chigi Saracini Sector 2.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	no smoke control system	7,00	7,29	7,63	8,23
	IF 1.2 detection system	no detection system	9,0			
	IF 1.3 suppression system	no automatic system and portable extinguish eq. not in every room, Fire service at law minimum compliance. No portable equipment in the other part of the sector except that in the highest fire load rooms.	10,50			
	IF 1.4 alarm system	alarm bell in the sector	4,00			
IC2	IF 2.1 type of evacuation route	Windows and balcony cannot be used as evacuation route, evacuation route used for"third priority" Works of Art	8,36	6,48	6,20	4,67
	IF 2.2 dimensions and layout	max. travel distance >30m; 2 levels to walk; not protected stairs	5,50			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	3,00	3,00	3,00
	IF3.2 horizontal structure	stone, bricks	3,00			
				OB1	OB2	OB3
			RI	5,95	5,75	5,90

Table 7.32: Risk Indexes for Sector 2 of Palazzo Chigi Saracini in actual situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	performant smoke control system	2,00	1,58	1,78	1,77
	IF 1.2 detection system	Laser detection System or Air sampling detection system everywhere	1,00			
	IF 1.3 suppression system	best FSI, audit for maintenance, gas system in rooms with valuable contents and portable extinguish in every room	2,37			
	IF 1.4 alarm system	spoken signal sent manually to all building	2,20			
IC2	IF 2.1 type of evacuation route	evacuation route used for "third priority" Works of Art	8,36	6,48	6,20	4,67
	IF 2.2 dimensions and layout	max. travel distance >30m; 2 levels to walk; not protected stairs	5,50			
	IF 2.3 linings and floorings	stone	2,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	3,00	3,00	3,00
	IF3.2 horizontal structure	stone, bricks	3,00			
				OB1	OB2	OB3
			RI	4,53	3,53	2,67

Table 7.33: Risk Indexes for Sector 2 of Palazzo Chigi Saracini in best situation.

7.2.5 Sector 3: musical instruments museum

Musical instruments museum is located at ground floor of the building and the main entrance to the museum is from via di città. The windows of the museum are instead in the back side of Palazzo Chigi Saracini, facing via Casato di Sotto; evacuation route leads to two independent exits. Such observations are considered in Sector 3 analysis. Figures 7.28 shows the location of musical instruments museum in the building plan.

Figure 7.28: Musical instruments museum at ground floor.

Table 7.34 shows risk indexes for Sector 3 of Palazzo Chigi Saracini in the actual situation.

Table 7.35 shows risk indexes for Sector 3 of Palazzo Chigi Saracini in best situation. Figure 7.29 shows relative representation of risk indexes for Palazzo Chigi Saracini Sector 3. No one of the three Risk Indicators for the Objectives is in the "acceptable area".

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	no smoke control system	7,00	5,63	5,88	6,46
	IF 1.2 detection system	wired smoke detectors (one in every room)	7,50			
	IF 1.3 suppression system	no automatic system and portable extinguish eq. not in every room, Fire service at law minimum compliance. No portable equipment in the other part of the sector except that in the highest fire load rooms.	10,50			
	IF 1.4 alarm system	alarm bell in the sector	4,00			
IC2	IF 2.1 type of evacuation route	Escape route leading to two independent staircases, more than 1 window can be used to evacuate, evacuation route used for“third priority” Works of Art	5,50	5,50	5,50	5,50
	IF 2.2 dimensions and layout	max. travel distance >30m; 2 levels to walk; not protected stairs	5,50			
	IF 2.3 linings and floorings	Textile wall cover	5,50			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	5,51	5,80	6,21

Table 7.34: Risk Indexes for Sector 3 of Palazzo Chigi Saracini in the actual situation.

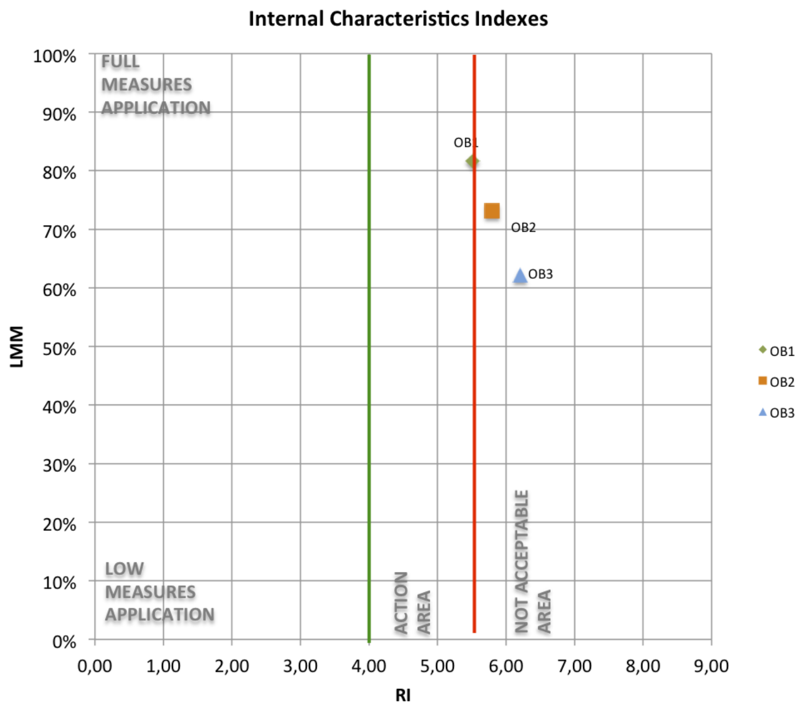


Figure 7.29: Relative representation of the risk indexes for Palazzo Chigi Saracini Sector 3.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	performant smoke control system	2,00	1,58	1,78	1,77
	IF 1.2 detection system	Laser detection System or Air sampling detection system everywhere	1,00			
	IF 1.3 suppression system	best FSI, audit for maintenance, gas system in rooms with valuable contents and portable extinguish in every room	2,37			
	IF 1.4 alarm system	spoken signal sent manually to all building	2,20			
IC2	IF 2.1 type of evacuation route	Escape route leading to two independent staircases, more than 1 window can be used to evacuate, evacuation route used for "third priority" Works of Art	5,50	5,50	5,50	5,50
	IF 2.2 dimensions and layout	max. travel distance >30m; 2 levels to walk; not protected stairs	5,50			
	IF 2.3 linings and floorings	Textile wall cover	5,50			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	4,50	4,24	3,86

Table 7.35: Risk Indexes for Sector 3 of Palazzo Chigi Saracini in best situation.

7.2.6 Sector 4: main museum

Main museum is located at first floor of the building with respect to the entrance from via di città while the secondary exit leads to via Casato di Sotto, corresponding to the second underground floor. In the museum there is a lack of portable equipment for fire suppression. Figures 7.30 shows the location of main museum in the building plan.

Figure 7.30: Main museum at first floor.

Table 7.36 shows risk indexes for Sector 4 of Palazzo Chigi Saracini in the actual situation.

Table 7.37 shows risk indexes for Sector 4 of Palazzo Chigi Saracini in the best situation.

Figure 7.31 shows relative representation of risk indexes for Palazzo Chigi Saracini Sector 4. No one of the three Risk Indicators for the Objectives is in the “acceptable area”.

For this sector, since it is the main museum with the most valuable contents in the building, an example of mitigation is here proposed. The Objective we choose to mitigate is the $OB3$: *fire and smoke spread*. According to Figure 6.6, to mitigate OB3 it is necessary to act on IC1. In this example we decided to simulate intervention only on IF1.3.3. FSI was increased from the “minimum law compliance” level to the “very good” level. Also IF1.3.4 parameter was increased to “maintenance with fire service audit”. It is to be noticed how only managerial strategies have been carried out.

In Table 7.38 risk indexes after OB3 mitigation are reported and in Figure 7.32 results after mitigation are shown. Table 7.39 shows data upon whom to build Figure 7.32.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	no smoke control system	7,00	5,63	5,88	6,46
	IF 1.2 detection system	wired smoke detectors (one in every room)	5,00			
	IF 1.3 suppression system	no automatic system and portable extinguish eq. not in every room, Fire service at law minimum compliance. No portable equipment in the other part of the sector except that in the highest fire load rooms.	7,50			
	IF 1.4 alarm system	alarm bell in the sector	4,00			
IC2	IF 2.1 type of evacuation route	Direct escape to two independent staircases, more than 1 window can be used to evacuate, evacuation route used for "second priority" Works of Art	5,59	5,55	5,55	5,52
	IF 2.2 dimensions and layout	max. travel distance >30m; 2 levels to walk; not protected stairs	5,50			
	IF 2.3 linings and floorings	Textile wall cover	5,50			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	5,54	5,81	6,21

Table 7.36: Risk Indexes for Sector 4 of Palazzo Chigi Saracini in the actual situation.

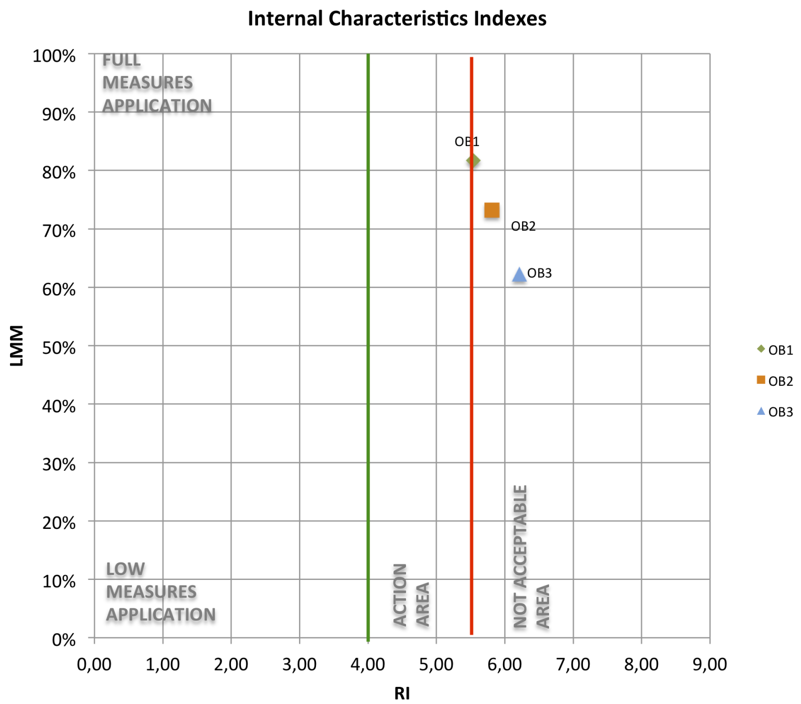


Figure 7.31: Relative representation of the risk indexes for Palazzo Chigi Saracini Sector 4.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	performant smoke control system	2,00	1,58	1,78	1,77
	IF 1.2 detection system	Laser detection System or Air sampling detection system everywhere	1,00			
	IF 1.3 suppression system	best FSI, audit for maintenance, gas system in rooms with valuable contents and portable extinguish in every room	2,37			
	IF 1.4 alarm system	spoken signal sent manually to all building	2,20			
IC2	IF 2.1 type of evacuation route	Direct escape to two independent staircases, more than 1 window can be used to evacuate, evacuation route used for "third priority" Works of Art	5,50	5,55	5,55	5,52
	IF 2.2 dimensions and layout	max. travel distance >30m; 2 levels to walk; not protected stairs	5,50			
	IF 2.3 linings and floorings	Textile wall cover	5,50			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	4,53	4,25	3,87

Table 7.37: Risk Indexes for Sector 4 of Palazzo Chigi Saracini in the best situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	no smoke control system	7,00	5,63	5,88	6,46
	IF 1.2 detection system	wired smoke detectors (one in every room)	5,00			
	IF 1.3 suppression system	no automatic system and portable extinguish eq. not in every room, **Fire service very good**. **Maintenance by means of internal audit**. No portable equipment in the other part of the sector except that in the highest fire load rooms.	4,80			
	IF 1.4 alarm system	alarm bell in the sector	4,00			
IC2	IF 2.1 type of evacuation route	Direct escape to two independent staircases, more than 1 window can be used to evacuate, evacuation route used for "second priority" Works of Art	5,59	5,55	5,55	5,52
	IF 2.2 dimensions and layout	max. travel distance >30m; 2 levels to walk; not protected stairs	5,50			
	IF 2.3 linings and floorings	Textile wall cover	5,50			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	5,23	5,44	5,47

Table 7.38: Risk Indexes for Sector 4 after OB3 mitigation.

		Actual situation		*After OB3 mitigation*			
	BI	*RI*	*LMM*	*RI*	*LMM*	ΔRI	ΔLMM
OB 1	4,53	5,54	82%	5,23	87%	0,31	5%
OB 2	4,25	5,81	73%	5,44	78%	0,37	5%
OB 3	3,87	6,21	62%	5,47	71%	0,75	8%

Table 7.39: Data for relative representation of risk for Sector 4 after OB3 mitigation Palazzo Chigi Saracini.

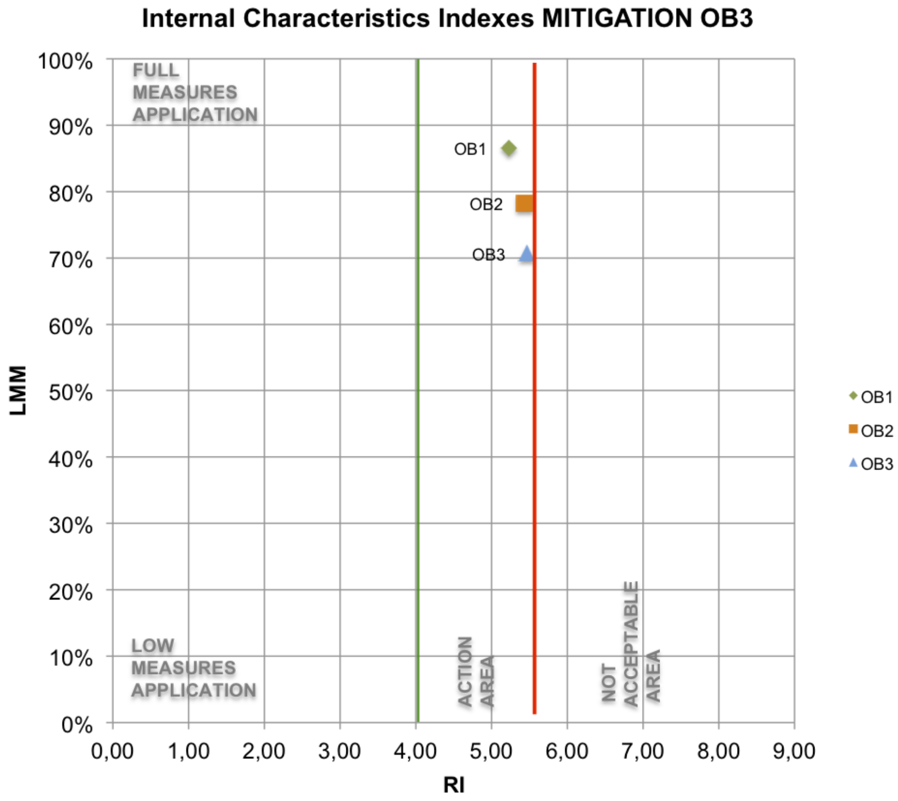


Figure 7.32: Relative representation of the risk indexes for sector 4 in Palazzo Chigi Saracini after mitigation of OB3.

From the above data it is possible to notice how the direct action on the $IC1 - Technical\ installations$ factor creates a reduction of the RI for Objective 3 and a significant increase of the corresponding LMM. At the same time there are also good secondary effects on the other two Objectives, both in terms of RI and LMM. At the end of the mitigation on OB3, also the other two Objectives come inside the "acceptable area".

7.2.7 Sector 5: quadreria

Quadreria is located at third floor of the building; it is a small museum only seldom open to the public that contains works of art more important than the ones in the main museum. Figure 7.33 shows the location of quadreria in the building plan.

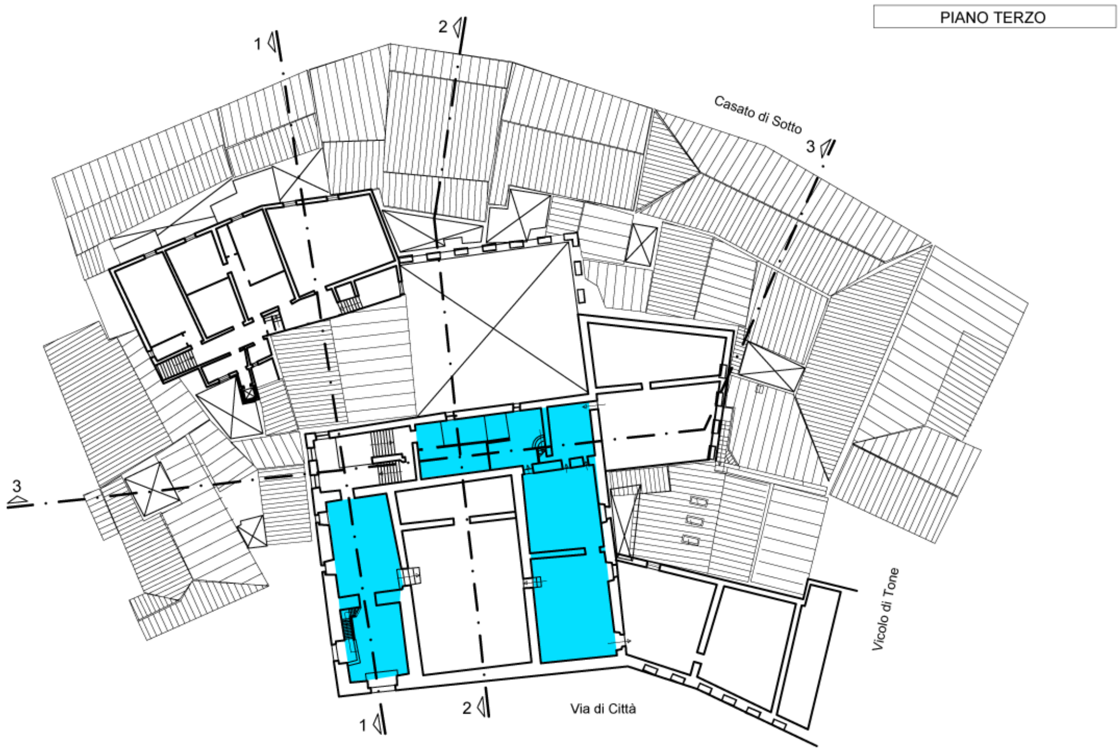


Figure 7.33: Quadreria at third floor.

Table 7.40 shows risk indexes for Sector 5 of Palazzo Chigi Saracini in the actual situation.

Table 7.41 shows risk indexes for Sector 5 of Palazzo Chigi Saracini in the best situation.

Figure 7.34 shows relative representation of risk indexes for Palazzo Chigi Saracini Sector 5. No one of the three Risk Indicators for the Objectives is in the “acceptable area” and the level of application of mitigation measures in quite high.

Also for this sector an example of mitigation is here proposed. The Objective we choose to mitigate is the $OB2 : \ fire\ brigade\ effectiveness$. According to Figure 6.5, to mitigate OB2 it is necessary to act firstly on IC3, then on IC2 and in the end on IC1. Intervention IC2 by means of management strategies. IF1.2.1 was turned in: wired smoke detectors more than one in every room and in every escape route, while IF1.3.3 was increased by changing FSI from“minimum law compliance” to “excellent”. Was also increased IF1.3.4 parameter to “maintenance with fire service audit”.

In Table 7.42 risk indexes after OB2 mitigation are reported and in Figure 7.35 results after mitigation are shown. Table 7.43 shows data upon which Figure 7.35 is built.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	no smoke control system	7,00	5,63	5,88	6,46
	IF 1.2 detection system	wired smoke detectors (one in every room)	5,00			
	IF 1.3 suppression system	nno automatic system and portable extinguish eq. not in every room, Fire service at law minimum comliance. No portable equipment in the other part of the sector except that in the highest fire load rooms.	7,50			
	IF 1.4 alarm system	alarm bell in the sector	4,00			
IC2	IF 2.1 type of evacuation route	One staircase may be used as an evacuation route, more than 1 window can be used to evacuate, evacuation route used for “first priority” Works of Art	5,59	7,71	7,55	6,32
	IF 2.2 dimensions and layout	max. travel distance >30m; 2 levels to walk; not protected stairs	9,60			
	IF 2.3 linings and floorings	Textile wall cover	5,50			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	6,71	6,41	6,35

Table 7.40: Risk Indexes for Sector 5 of Palazzo Chigi Saracini in actual situation.

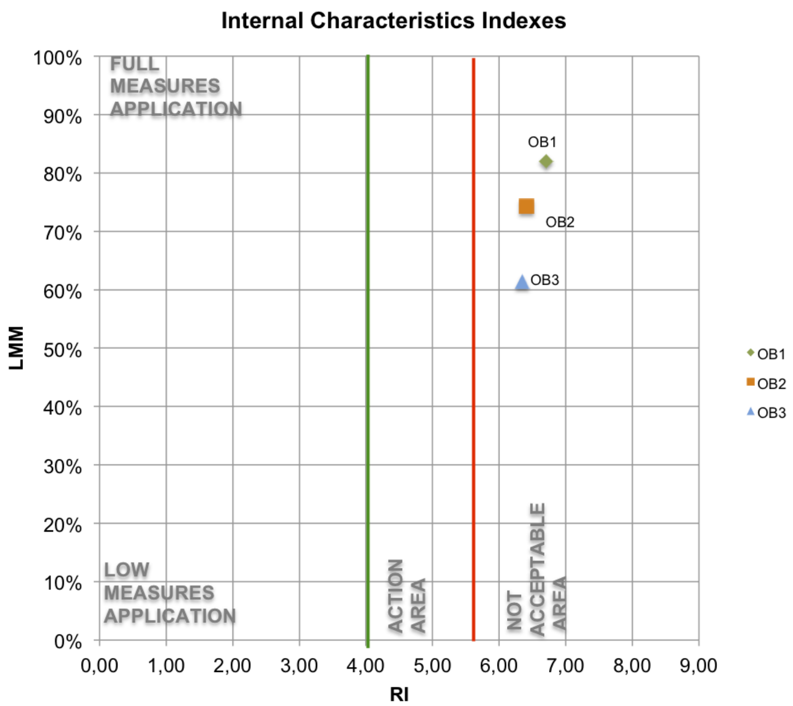


Figure 7.34: Relative representation of the risk indexes for Palazzo Chigi Saracini Sector 5.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	performant smoke control system	2,00	1,58	1,78	1,77
	IF 1.2 detection system	Laser detection System or Air sampling detection system everywhere	1,00			
	IF 1.3 suppression system	best FSI, audit for maintenance, gas system in rooms with valuable contents and portable extinguish in every room	2,37			
	IF 1.4 alarm system	spoken signal sent manually to all building	2,20			
IC2	IF 2.1 type of evacuation route	One staircase may be used as an evacuation route, more than 1 window can be used to evacuate, evacuation route used for "first priority" Works of Art	9,60	7,47	7,24	5,72
	IF 2.2 dimensions and layout	max. travel distance >30m; 2 levels to walk; not protected stairs	5,50			
	IF 2.3 linings and floorings	Stone	4,00			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	5,56	4,76	3,90

Table 7.41: Risk Indexes for Sector 5 of Palazzo Chigi Saracini in the best situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	no smoke control system	7,00	3,52	3,93	4,04
	IF 1.2 detection system	**wired smoke detectors more than one in every room and in every escape route**	2,50			
	IF 1.3 suppression system	no automatic system and portable extinguish eq. not in every room, **Fire service excellent and internal audit for maintenance**. No portable equipment in the other part of the sector except that in the highest fire load rooms.	3,20			
	IF 1.4 alarm system	alarm bell in the sector	4,00			
IC2	IF 2.1 type of evacuation route	One staircase may be used as an evacuation route, more than 1 window can be used to evacuate, evacuation route used for "first priority" Works of Art	5,59	7,71	7,55	6,32
	IF 2.2 dimensions and layout	max. travel distance >30m; 2 levels to walk; not protected stairs	9,60			
	IF 2.3 linings and floorings	Textile wall cover	5,50			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	6,18	5,67	5,14

Table 7.42: Risk Indexes for Sector 5 after OB2 mitigation.

		Actual situation		*After OB2 mitigation*			
	BI	*RI*	*LMM*	*RI*	*LMM*	ΔRI	ΔLMM
OB 1	5,50	6,71	82%	6,18	89%	0,53	7%
OB 2	4,76	6,41	74%	5,67	84%	0,74	10%
OB 3	3,90	6,35	61%	5,14	76%	1,21	14%

Table 7.43: Data for relative representation of risk for Sector 5 after OB2 mitigation in Palazzo Chigi Saracini.

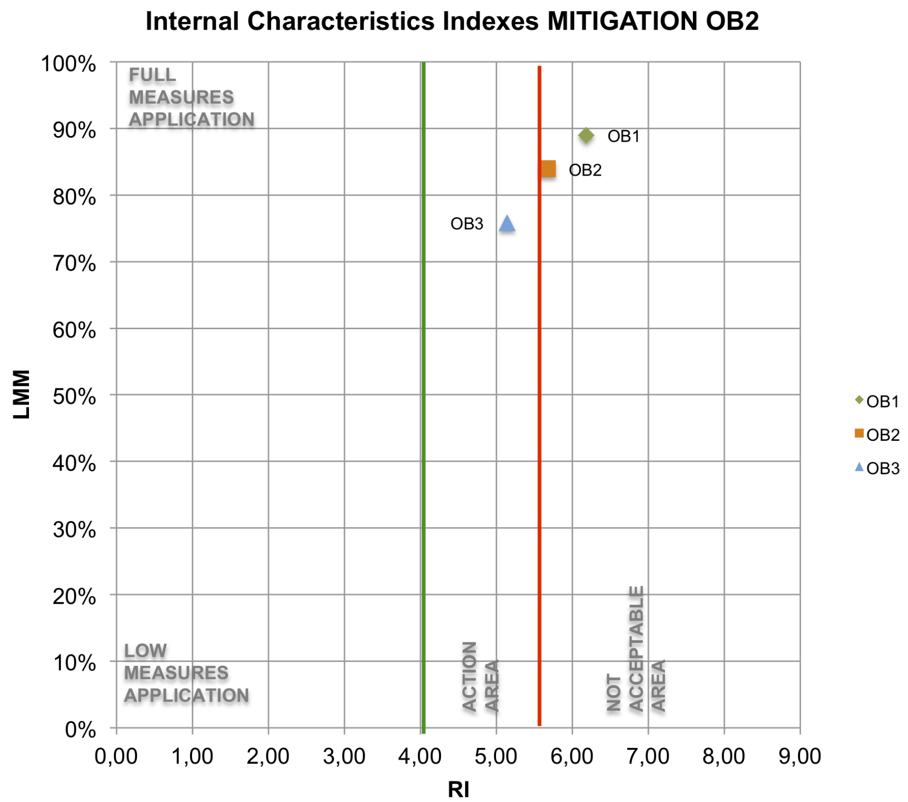


Figure 7.35: Relative representation of the risk indexes for sector 5 in Palazzo Chigi Saracini after mitigation of OB2.

From the above data it is possible to notice how the direct action on the $IC1 - Technical\ installations$ factor create a reduction of the RI for Objective 3 and a significant increase of the corresponding LMM. At the same time there are no good secondary effects on the other two Objectives. At the end of the mitigation on OB2, the other two Objectives don't come inside the "acceptable area". It is possible in this case to start again a mitigation path in order to reduce OB2 an OB1 RI, according to Figures 6.5 and 6.4.

7.2.8 Sector 6: theatre

Theatre is located on two different levels: stalls occupy a part of the first floor while gallery is at the second floor of the building. When the theatre is open, no other activity is carried on inside the building and we make the assumption that Fire Service team works exclusively for the theatre. In the theatre there are valuable contents as pictures and furniture linked with the history of the building.

Figures 7.36 and 7.37 show the location of the theatre in the building plan.

Figure 7.36: Theatre at first floor.

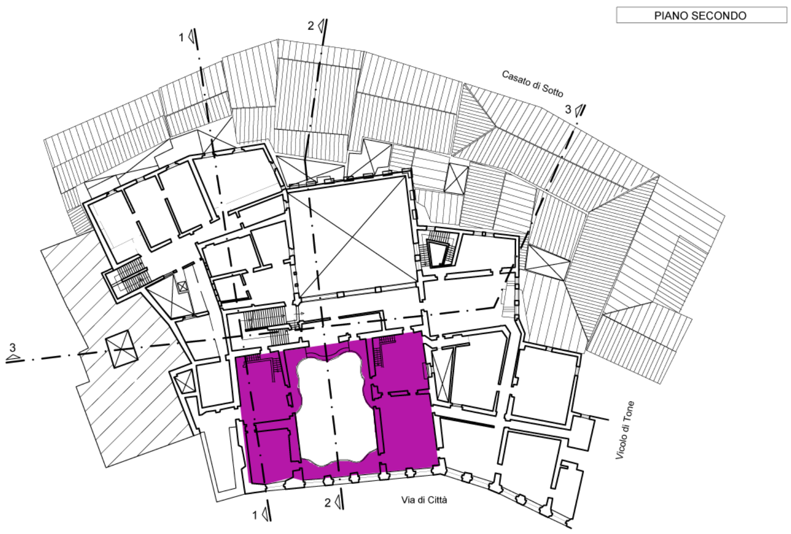


Figure 7.37: Theatre at second floor.

Table 7.44 shows risk indexes for Sector 6 of Palazzo Chigi Saracini in the actual situation.

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	no smoke control system	7,00	4,80	5,00	5,57
	IF 1.2 detection system	More than one wired smoke detector in every room	3,00			
	IF 1.3 suppression system	no automatic system and portable extinguish eq. not in every room, Fire service higher than minimum compliance (because of the public event). No portable equipment in the other part of the sector except that in the highest fire load rooms.	6,00			
	IF 1.4 alarm system	alarm bell in the sector	4,00			
IC2	IF 2.1 type of evacuation route	Escape route leading to two independent staircases, more than 1 window can be used to evacuate, evacuation route used for "third priority" Works of Art	5,00	5,23	5,25	5,40
	IF 2.2 dimensions and layout	max. travel distance >30m; 2 levels to walk; not protected stairs	5,50			
	IF 2.3 linings and floorings	Textile wall cover	5,50			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	3,00	3,00	3,00
	IF3.2 horizontal structure	stone, bricks	3,00			
				OB1	OB2	OB3
			RI	4,65	4,47	4,69

Table 7.44: Risk Indexes for Sector 6 of Palazzo Chigi Saracini in the actual situation.

Table 7.45 shows risk indexes for Sector 6 of Palazzo Chigi Saracini in the best situation.

Figure 7.38 shows relative representation of risk indexes for Palazzo Chigi Saracini Sector 6. All the three Risk Indicators for the Objectives are in the "acceptable area".

Characteristic	*Factor*	*Description*		OB1	OB2	OB3
IC1	IF 1.1 smoke control system	performant smoke control system	2,00	1,58	1,78	1,77
	IF 1.2 detection system	Laser detection System or Air sampling detection system everywhere	1,00			
	IF 1.3 suppression system	best FSI, audit for maintenance, gas system in rooms with valuable contents and portable extinguish in every room	2,37			
	IF 1.4 alarm system	spoken signal sent manually to all building	2,20			
IC2	IF 2.1 type of evacuation route	Escape route leading to two independent staircases, more than 1 window can be used to evacuate, evacuation route used for “third priority” Works of Art	5,00	5,23	5,25	5,40
	IF 2.2 dimensions and layout	max. travel distance >30m; 2 levels to walk; not protected stairs	5,50			
	IF 2.3 linings and floorings	Textile wall cover	5,50			
IC3	IF 3.1 vertical structure	stone, bricks	3,00	5,40	5,80	6,20
	IF3.2 horizontal structure	wood	7,00			
				OB1	OB2	OB3
			RI	3,85	3,24	2,79

Table 7.45: Risk Indexes for Sector 6 of Palazzo Chigi Saracini in the best situation.

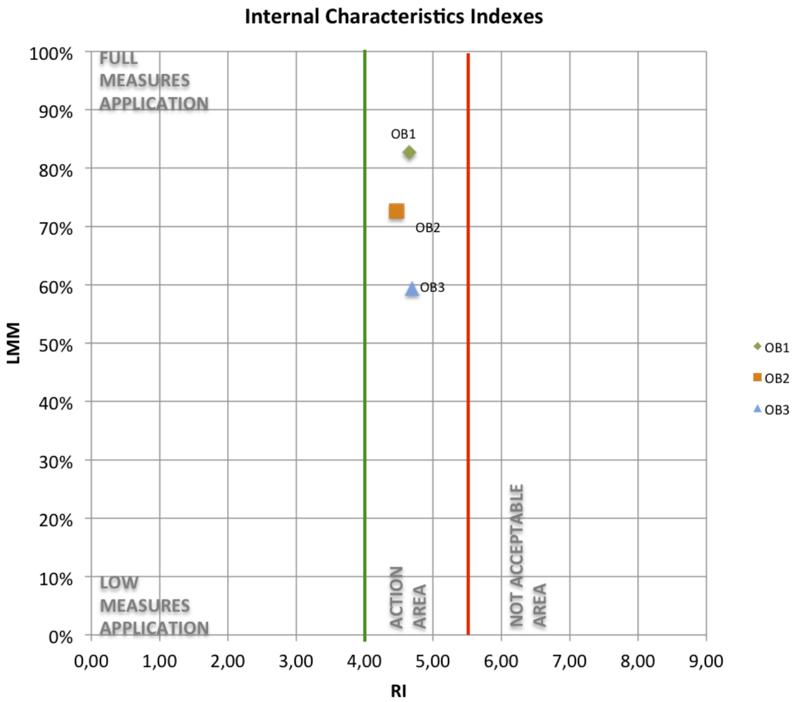


Figure 7.38: Relative representation of the risk indexes for Palazzo Chigi Saracini Sector 6.

7.2.9 Remarks on Palazzo Chigi Saracini case study

Palazzo Chigi Saracini has a very complex architectonical configuration and distribution; such feature is a contemporary source of advantages and disadvantages. In terms of External Characteristics, complexity in vertical connections makes the number of stairs for evacuation and fire brigade effectiveness sufficient , while such complexity creates a high risk index in fire and smoke spread. At the same time, the almost total lack of technical installations creates high risk indexes in most sectors, with respect to the Internal Characteristics. Another important remark is related with Fire Service Team: there is the necessity to increase the number of components of the team and their level of formation.

7.3 OPD and Palazzo Chigi Saracini: a comparison

After the procedure application to the two case studies, two different remarks have to be done: one in order to compare results from the procedure with the real expectations, and one in order to compare results from the two different building.

Table 7.46 shows a resume of the results from case studies.

	Opificio delle Pietre Dure (OPD)	*Palazzo Chigi Saracini*
External Characteristics	It is a "simple building" with very precious contents	It is a very complex building, not wholly suitable to host all the different activities it hosts
Expectations	We expect to have no problems from the External Characteristics evaluation	We expect to have problems from the External Characteristics evaluation
Results	All the indicators are acceptable	One indicator is not acceptable
Concordance between results and expectations	YES	YES
Internal Characteristics	Building has a good system of egress paths, fire compartments and a very good technical system for fire prevention and protection. Fire Service team is well prepared	Building has a lot of different destinations of use and most of the sectors share the same egress paths. Almost total absence of technical systems for fire prevention and protection. Fire service team is not well prepared.
Expectations	We expect to have no problems from the Internal Characteristics evaluation	We expect, in some Sectors, to have problems from the External Characteristics evaluation
Results	All the indicators are acceptable	Only few indicators in each Sector are acceptable
Concordance between results and expectations	YES	YES

Table 7.46: Resume of the results from case studies.

Fire protection plan of Palazzo Chigi Saracini is now in progress, technicians and fire brigades are still working on a suitable design for this particular building in order to join prescriptions from fire codes with fire safety engineering models. The Risk Management Procedure was applied on Palazzo Chigi Saracini taking into account only the actual situation and expecting to find out about the same suggestion in mitigation that is included in the fire protection project. Even if FRMP and official fire design have different goals (protection of contents vs protection of human life) a good concordance between them was realized. Both the procedure and the preliminary results from design suggest that the number of stairs for evacuation is enough, since the low number of occupants. Then there is concordance also in the decision to improve technical installations, with a specific attention to the fire suppression installations both mobile and fixed. FRMP further suggests to improve the reliability level of the Fire Service Team (increasing the number and level of formations of the members) in order to assure a smart intervention both in life safety and contents protection.

From technicians and fire brigades, OPD base in Fortezza da Basso is considered to be a virtuous example of ancient building with an high degree of fire protection measure's implementation. OPD base respects most of the prescriptions of Italian fire codes; moreover, thanks to a good management, OPD workers have an high sensibility in fire protection both for human life and for contents. FRMP confirms such theory with output Risk Indexes totally acceptable both for the External Characteristics and for the Internal ones.

We can then make the hypothesis of a manager that has to administrate both the buildings, in this situation (not corresponding to reality) the manager could be interested in a direct comparison between the risk indicators of the two buildings. Let's compare External Characteristics of the two buildings with respect to *OB1- Evacuation*: using representations in section 6.3.3, it is possible to depict the situation as shown in Figure 7.39 basing on data from Table 7.47. According to the meaning of such representation, we can realize how much more room for improvement there is in OPD building with respect to Palazzo Chigi Saracini. Even if OPD has lower risk indexes, it is the building that can be made safer because of its simple architectonical features; Palazzo Chigi Saracini has, from the procedure, higher risk indexes but also lower possibilities to be improved in terms of contents protection with respect to OB1.

		Actual situation	*Best situation*
Opificio delle Pietre Dure	ΔR	0,99	3,41
	MMT	54%	0%
Palazzo Chigi Saracini	ΔR	1,74	1,99
	MMT	7%	0%

Table 7.47: Data for comparison among the buildings with respect to Objective 1.

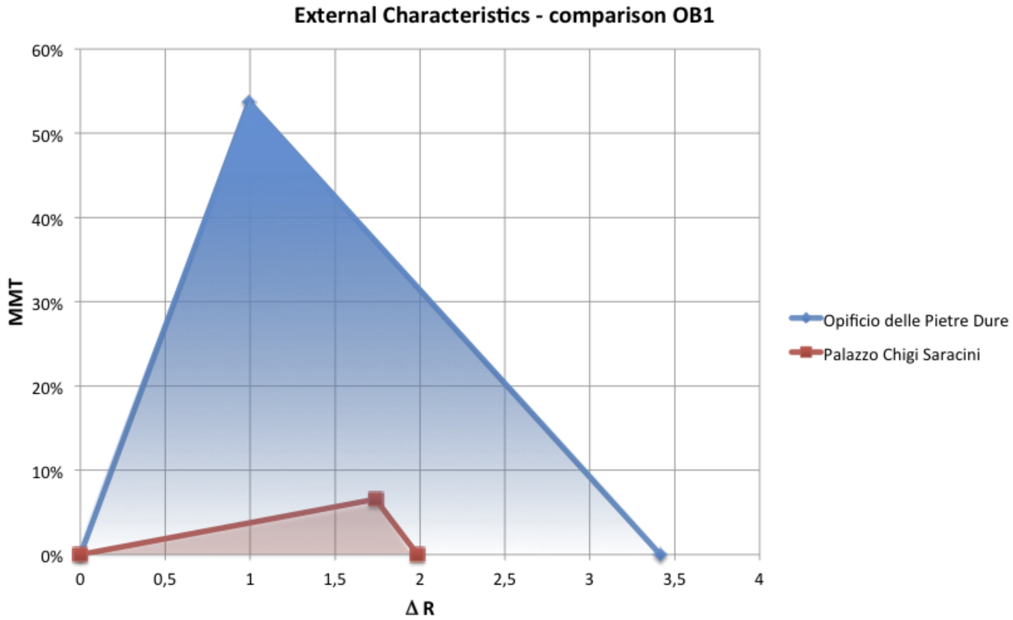


Figure 7.39: Comparison of the two buildings: External Characteristics with respect to *OB1-Evacuation.*

Now let's compare External Characteristics of the two buildings with respect to *OB3-Fire and smoke spread* using the above representation. From Figure 7.40 based on data from Table 7.48, it is possible to perceive the almost equivalent surface of the two areas.

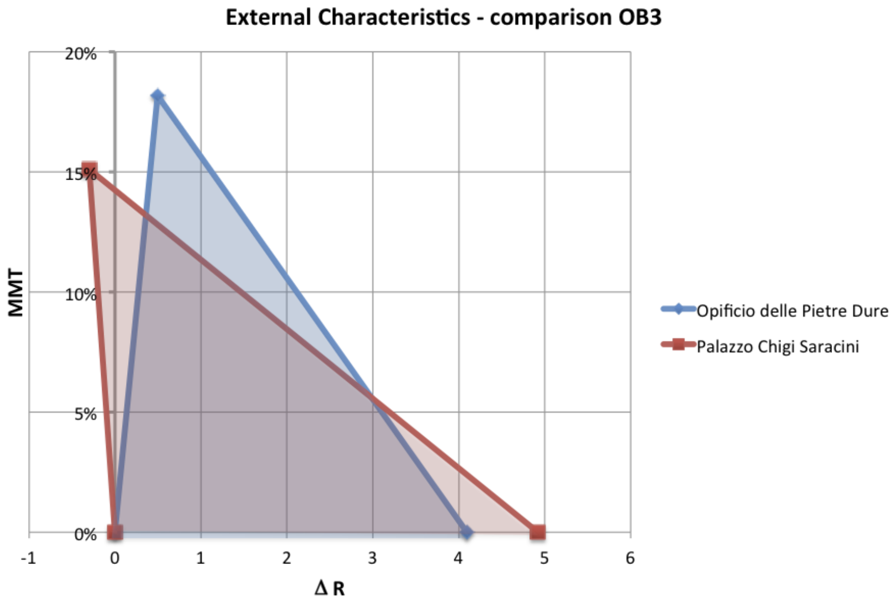


Figure 7.40: Comparison of the two buildings: External Characteristics with respect to *OB3-Fire and smoke spread.*

In such case, the manager has to act in order to eliminate negative ΔR, that represents

		Actual situation	*Best situation*
Opificio delle Pietre Dure	ΔR	0,49	4,10
	MMT	18%	0%
Palazzo Chigi Saracini	ΔR	-0,30	4,92
	MMT	15%	0%

Table 7.48: Data for comparison among the buildings with respect to Objective 3.

a not acceptable risk index for the actual situation. In case of $\Delta R < 0$, the first action to be taken is to mitigate the corresponding RI for that Objective, moving the area in the positive quadrant.

Chapter 8

Summary, Contributions and Recommendations

The main body of the thesis ends in this chapter with a summary of key results, contributions to research and recommendations for future works.

8.1 Summary of Key Results and Contributions

The findings and contributions to research of this thesis are summarised below:

- **Fire Risk Management Procedure for Valuable Contents**. The Risk Management Procedure described in this dissertation is based on a semi-quantitative method of risk assessment associated to a risk treatment method that proposes packages of measure to mitigate risk. The main goal of the procedure is to protect Valuable Contents but important secondary effects are beneficial also for the historical building with respect to fire risk. The reliability of the procedure is enclosed in the set of parameters chosen for the AHP and in the judgments of relative importance given to the parameters. To start up the procedure, such reliability has been assured by means of Delphi method: experts have been involved in the hierarchical structure's architecture and in the formulation of judgments. Because of the origin of the experts panels, the proposed procedure assumes its maximum reliability and effectiveness if applied to the Italian situation, especially in the Tuscany region (area that is marked by homogeneous historical building's features and similar management strategies).

- **Validation of the Procedure**. Fire Risk Management Procedure is built up on a structure that is fed by expert's judgments; such procedure has been tested on two buildings and the validity of the results was this way confirmed. The building we chose to test the Procedure represents two opposite examples both in terms of architectonical features, and technical installations and valuable contents hosted inside them. We tried this way to take into account two limit cases representing the extremes of a wide gamma of buildings in Tuscany.

- **An *easy-to-use* management instrument**. Historical Building's manager is the first addressee of the Procedure and choice of a simple method, graphically user friendly, makes it an *easy-to-use* instrument. Great attention was put in risk communication by means of different output representation useful to depict different aspects of the same output on the base of the decision that has to be taken from the manager. "Annex A" gives a practical guideline to use the Procedure.

8.2 Recommendations for Future Works

The research objectives outlined for this thesis end in this chapter. However, several questions still remain to be answered in future works:

- **Improve reliability of the Procedure and further calibration**. To improve reliability of the Procedure implies to calibrate again weights and risk indexes in the AHP structure on the base of the evidence coming out from the application. The structure of the Procedure (both of Risk Analysis Method and Risk Treatment Method) is "open"; connections among parameters are established but weights for their combination can be constantly updated. It is then possible, if future development requests it, to add further parameters to the Hierarchic Structure in order to perform a more accurate analysis. It is to remember that, as an intrinsic characteristic of the semi-quantitative method is here used, increasing the number of parameters means to reduce importance of each one of the other parameters. Risk indexes coming out from the Procedure are not a measure of the absolute fire safety level, but a rough indicator of whether the building is safer than other buildings or not. The Procedure also very well illustrates different ways of enhancing the fire safety level and can be used to compare different options. Receiving a risk index lower than the acceptable risk level, obviously is not a guarantee that the building fulfills the current building regulations. The hierarchic structure can therefore be fed in future by more accurate judgments calibrated again on the basis of further results that could be non in concordance with the real situation.

- **Applicability in other geographical contexts**. As widely said, Procedure described in this dissertation has a well known boundary: the geographical context onto which Procedure has been calibrated. A first limit can be pointed out in the choice of the AHP parameters: different building traditions can determine a different set of parameters to be considered in fire protection for contents inside historical buildings. As example of such assertion we can adduct the "fire wall": it is an architectonical feature widely present in other countries (i.e. Germany or England) while it is almost impossible to find in Italy. If we want to apply the Procedure in different countries, such peculiar parameters have to be taken into account. Delphi's panel used in this dissertation is another limit for the applicability *tout court* of the Procedure in other countries. All the experts have been identified in the Tuscan context with the aim to increase reliability of the Procedure in that defined context. This choice implies a lack of reliability for all the application outside the original boundary of validation. Calibration of the Procedure for different geographical contexts needs to foresee:

1. definition of a specific set of parameters for the hierarchic structure;
2. attribution of weights by means of a Delphi method performed in that context;
3. validation trough the Procedure application to chosen case studies significant for the context.

- **Insurance application**. Important relationships can be established between risk indexes coming from the Procedure and the insurance premium to be payed for contents. It is important for insurance companies to find criteria to count risk, apart from the correspondence between the measurement and the real situation. The risk scale proposed in the Procedure, used as a relative risk scale, can be useful for this aim. Representation of the risk by means of "mitigation path", as referred on page 164, can be used to individuate future milestones in contents protection, linking the premium amount to the achievement of such targets. The manager can cope with the insurance companies in order to make the premium proportional to the Risk Index of a specific Sector (or of the whole building), with respect to the possible mitigation measures he can take. The more a manger can demonstrate to invest in contents protection tending to reach milestones in mitigation paths, the more insurance premium can be reduced.

  Building's manager can measure the risk and can have a path to follow in order to reduce it; insurance companies can reward virtuous managers allowing reduction of premiums or obliging managers to act in order to reduce risk for contents.

  Future development of the Procedure can be done making a direct connection between output in terms or Risk Indexes, Measure of Mitigation to be taken and the amount of insurance premium.

Appendix A

GUIDELINES

This annex provides guidelines that describe how to make practical use of the Fire Risk Management Procedure for Valuable Contents in Historical Heritage Buildings. Guidelines turn their attention to the building managers and take into account which are the data to be collected before running the procedure and how to input them into the spreadsheets in order to have results. As starting point it is necessary to became familiar with the building knowing its history and architectonical evolution trough centuries. Before starting to apply procedure, manager has to be able to individuate in the building the suitable number of Sectors to be analysed. A *Sector* has to be identified as:

- part of the building with the same destination of use;
- part of the building that is a single architectonical unit (a building's level, a single special room - a theatre, an hall, a double height salon- , a series of rooms with common features);
- part of the building that is a fire compartment (with respect to the regulation definition).

Data useful to the procedure can be collected by means of check-lists that are composed by two parts:

- Part 1: External Characteristics. This part has to be completed once for the building with respect to the External Characteristics;
- Part 2: Internal Characteristics. This check list has to be completed many times as are the Sectors.

In the follow *fac-simile* of data collection check-lists are reported.

A.1 CHECK LIST PART 1: EXTERNAL CHARACTERISTICS

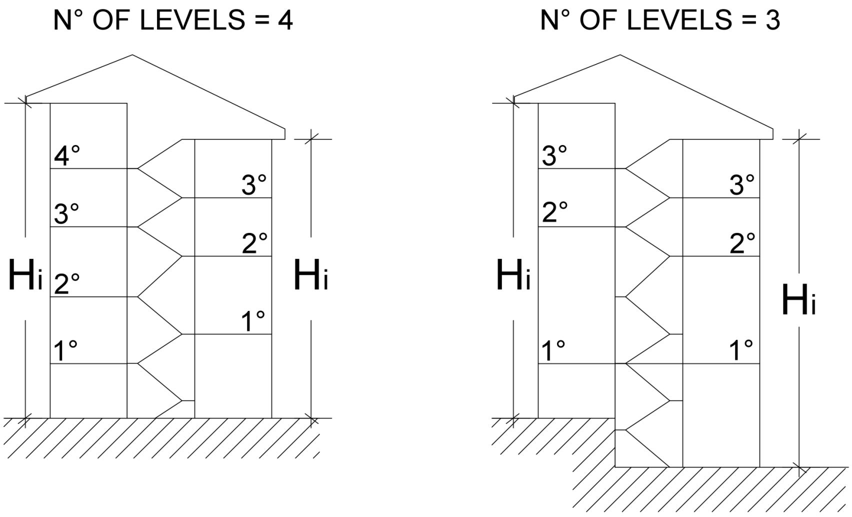
EC1 HEIGHT

EF 1.1 Levels
If the building has staggered floors, the number of levels is calculated looking at the façade with the higher number of levels.

N° OF LEVELS	CHECK BOX
1	
2	
3	
> 3	

N° OF UNDERGROUND LEVELS		CHECK BOX
NO UNDERGR. LEV.		
YES	1	
	2	

ATTIC		CHECK BOX
NO ATTIC		
YES	empty	
	with technical installation inside	

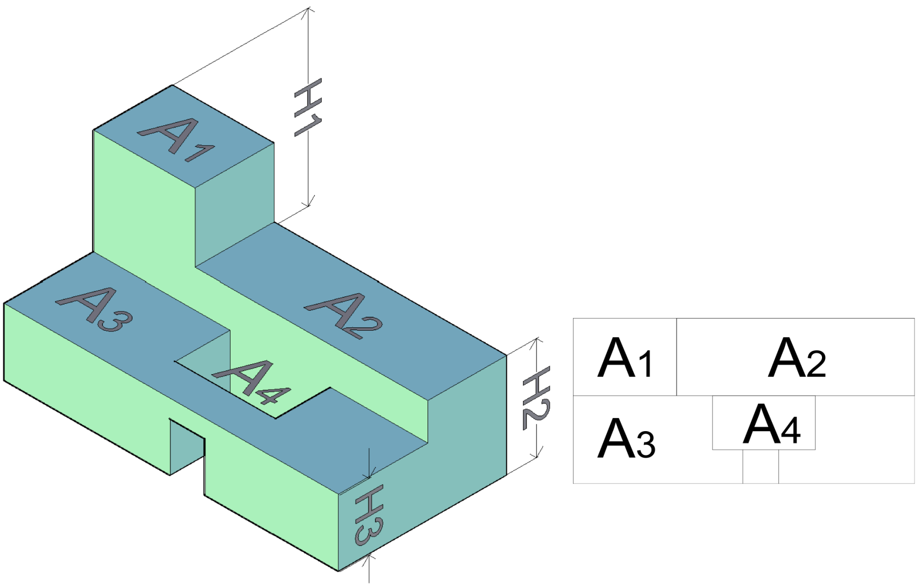


EF 1.2 Medium height

Height is always calculated under the eaves.

- A_i is the surface (in m^2) of the corresponding part of the building with H_i height
- H_i is the height (in m) of the corresponding part of the building with A_i surface
- If H_i =0 we are considering "empty" areas (courtyards, ….)

HEIGHT [m]		CORRESPONDING SURFACE [m^2]		open to the public	partially open to the public	not open to the public
H1		A1				
H2		A2				
H3		A3				
H4		A4				
H5		A5				
Hn		An				



EC2 VERTICAL CONNECTIONS

EF 2.1 Stairs

STAIRS		CHECK BOX
E_{tot}	total n° existing stairs	
E_{SS}	n° of safe egress stairs	
E_{ES}	n° of equivalent safe egress stairs	
D_S	ideal number of emergency stairs	

EF 2.2 Double Heights

DOUBLE HEIGHTS	CHECK BOX
NO	
1 DOUBLE HEIGHT: 2 levels HEIGTH	
1 DOUBLE HEIGHT: 3 levels HEIGTH	
> 1 DOUBLE HEIGHT	

Flues and chimneys	CHECK BOX
NO	
Spread flues and chimneys directly detected	
Possible presence of ancient flues and chimneys	

EC3 CONTEXT

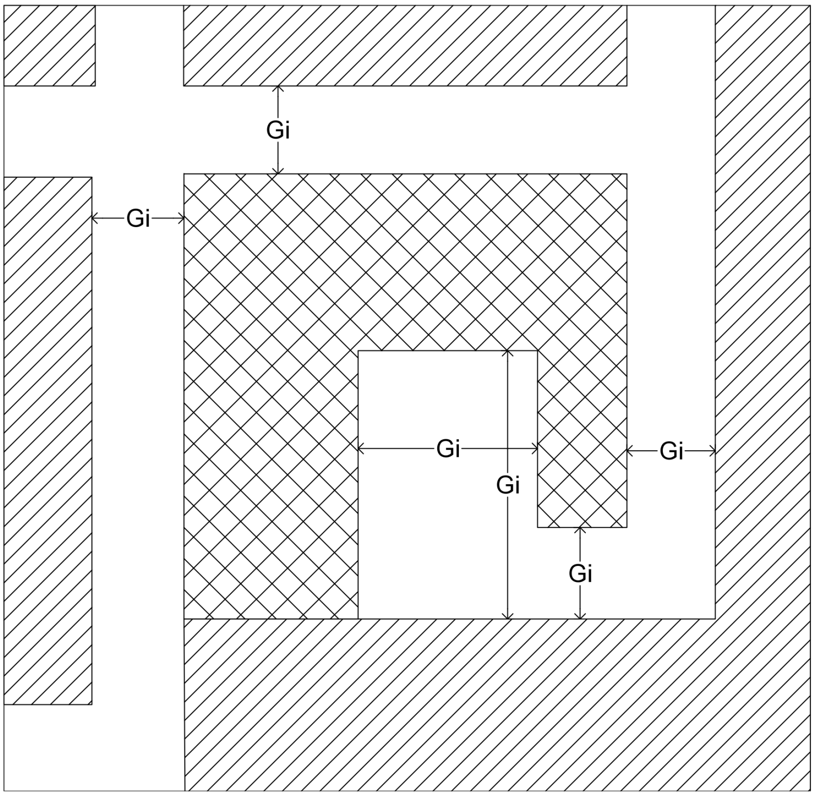
EF 3.1 Fire brigade response time

FIRE BRIGADE RESPONSE TIME	CHECK BOX
0-5 min (on site fireman)	
5-10 min	
10-15 min	
> 15 min	

EF 3.2 Surroundings

Number of sides/facades of the building	

		Accessibility of each side				
SIDE	Distance between facade and opposite buildings	Not accessible	less than 1 window for each level accessible	1 window for each level accessible	More than 1 window for each level accessible	All windows for each level accessible
SIDE n	Gi < 3,5m - not accessible for the fire brigades' truck					
	3,5 ≤ Gi ≤ 6m					
	6 < Gi ≤ 9m					
	9 < Gi ≤ 20m					
	20m > Gi					



BUILDING LOCATION	CHECK BOX
URBAN LOCATION	
IN HISTORICAL CENTRE and TRAFFIC RESTRICTED AREA	
IN HISTORICAL CENTRE	
OUTSIDE HISTORICAL CENTRE	

FSI EXTRA FACTOR

FSI 1 - Number of fire service memebers for each sector

Sector	Number of members in each sector	CHECK BOX
sector 1	> 1	
	= 1	
	0	
sector 2	> 1	
	= 1	
	0	
sector n	> 1	
	= 1	
	0	

FSI 2 - Level of formation

LEVEL OF FORMATION		CHECK BOX
A	Low Fire Risk (4h)	
B	Medium Fire Risk (8h)	
C	High Fire Risk (16h)	

FSI 3 - Retraining

RETRAINIG	theorical and practical	only practical	only theorical
every year			
every two years			
every three years			

A.2 CHECK LIST PART 2: INTERNAL CHARACTERISTICS

IC1 TECHNICAL INSTALLATIONS

IF 1.1 Smoke control system

Type of smoke control	CHECK BOX
Natural ventilation through openings near ceiling	
Mechanical ventilation	
Pressurisation and natural or mechanical or mixed ventilation for exiting smoke	

Activation of smoke control system	CHECK BOX
Automatically	
Manually	
No smoke control system	

MAINTENANCE	CHECK BOX
once a year	
twice a year	

IF 1.2 Detection system

Detectors in rooms/compartments	CHECK BOX
None in the rooms	
At least one in every room	
More than one in every room	
Detectors in the escape route	**CHECK BOX**
NO	
YES	

Type of detectors		CHECK BOX
Heat detectors	Wireless	
	Wired	
Smoke detectors	Wireless	
	Wired	
Heat and smoke detectors with CPU on board	Wireless	
	Wired	
Laser detection System or Air sampling detection system		

MAINTENANCE	CHECK BOX
once a year	
twice a year	

IF 1.3 Suppression system

Automatic system		
Location	Type	CHECK BOX
in rooms/compartments with highest fire load	No automatic system	
	Sprinkler	
	Gas system	
	Special system (i.e. watermist)	
in rooms/compartments with valuable contents	No automatic system	
	Sprinkler	
	Gas system	
	Special system (i.e. watermist)	
in the remaining parts of the analysed sector	No automatic system	
	Sprinkler	
	Gas system	
	Special system (i.e. watermist)	

Portable equipment	CHECK BOX
None	
Extinguishing eq. NOT in every room	
Extinguishing eq. in every room	

MAINTENANCE	CHECK BOX
once a year	
twice a year	
internal audit	

IF 1.4 Alarm system

Sound signal	CHECK BOX
No	
Alarm bell	
Spoken signal	

Light signal	CHECK BOX
No	
Yes	

Location	CHECK BOX
signal only in the room/compartment	
signal sent manually at the whole building	

IC2 EGRESS PATHS

IF 2.1 Type of evacuation routes

<table>
<tr><th colspan="4">External evacuation routes: Window/balcony</th><th rowspan="2">CHECK BOX</th></tr>
<tr><th>Windows and balcony cannot be</th><th>Number</th><th colspan="2">Dimensions and characteristics</th></tr>
<tr><td rowspan="4">windows</td><td rowspan="2">1</td><td colspan="2">NOT at ground floor</td><td></td></tr>
<tr><td colspan="2">at ground floor</td><td></td></tr>
<tr><td rowspan="2">> 1</td><td colspan="2">NOT at ground floor</td><td></td></tr>
<tr><td colspan="2">at ground floor</td><td></td></tr>
<tr><td rowspan="8">balcony</td><td rowspan="4">1</td><td rowspan="2">surface ≥ 3,5m x 3,5m</td><td>reachable with a permanent stair</td><td></td></tr>
<tr><td>reachable with a Fire Brigade Ladder</td><td></td></tr>
<tr><td rowspan="2">surface < 3,5m x 3,5m</td><td>reachable with a permanent stair</td><td></td></tr>
<tr><td>reachable with a Fire Brigade Ladder</td><td></td></tr>
<tr><td rowspan="4">> 1</td><td rowspan="2">surface ≥ 3,5m x 3,5m</td><td>reachable with a permanent stair</td><td></td></tr>
<tr><td>reachable with a Fire Brigade Ladder</td><td></td></tr>
<tr><td rowspan="2">surface < 3,5m x 3,5m</td><td>reachable with a permanent stair</td><td></td></tr>
<tr><td>reachable with a Fire Brigade Ladder</td><td></td></tr>
</table>

Staircases and internal connections	CHECK BOX
One staircase may be used as an evacuation route	
Escape route leading to two independent staircases	
Direct escape to two independent staircases	
Direct communication with at least one safe fire compartment at the same floor	

Importance of the work of art to be evacuated	CHECK BOX
Unclassified: items that will be left in place	
Third Priority: items that would be difficult or expensive to replace and which contribute to the history of the building	
Second priority: items of national value or which are important to explain the history of the building or its occupants. This should also include items that have a high monetary value	
First priority: items of international heritage value which are intimately connected with the building or its previous occupants	

IF 2.2 Dimensiones and layout

Maximum travel distance	CHECK BOX
$D \geq 30m$	
$15m \leq D < 30$ m	
$D < 15m$	

Staircases and internal connections	CHECK BOX
One staircase may be used as an evacuation route	
Escape route leading to two independent staircases	
Direct escape to two independent staircases	
Direct communication with at least one safe fire compartment at the same floor	

Importance of the work of art to be evacuated	CHECK BOX
Unclassified: items that will be left in place	
Third Priority: items that would be difficult or expensive to replace and which contribute to the history of the building	
Second priority: items of national value or which are important to explain the history of the building or its occupants. This should also include items that have a high monetary value	
First priority: items of international heritage value which are intimately connected with the building or its previous occupants	

IF 2.2 Dimensiones and layout

Maximum travel distance	CHECK BOX
D ≥ 30m	
15m ≤ D <30 m	
D < 15m	

IC3 MAIN STRUCTURE

IF 3.1 Vertical structure

Type of structure	SURFACE % ESTIMATION
STONE; CONCRETE	
WOOD	
STEEL	
PROTECTED WOOD	
PROTECTED STEEL	

IF 3.1 Horizontal structure

Type of structure	SURFACE % ESTIMATION
STONE; CONCRETE	
WOOD	
STEEL	
PROTECTED WOOD	
PROTECTED STEEL	

A.3 SPREADSHEETS INSTRUCTIONS

In this section, captions from Procedure's spreadsheets are reported. For each one of the Factors, tables are shown in order to explain to Procedure's user how to employ data from check-lists.

In columns marked with "Assigned", the user has to write down the risk index corresponding to the collected data, according to risk value listed in tables. Data have to be inserted only in boxes with gray background.

In boxes with red text, the user has to insert values coming from data collection as required from the table.

In boxes with light blu background, the user can find the output risk index for that factor that procedure will use to calculate risk indexes with respect to the Objectives.

EF1.1 Number of levels

The Factor that considers the number of building's levels is defined as follow:

$$EF1.1 = EF1.1.1 \times EF1.1.2 \times EF1.1.3 \tag{A.1}$$

where:

- *EF1.1.1* is the Sub-Factor dealing with the number of levels out of ground;
- *EF1.1.2* is the Sub-Factor considering the number of underground levels;
- *EF1.1.3* is the Sub-Factor considering the presence of an attic and its destination of use.

EF 1.1 **N° OF LEVELS**

EF1.1 = EF 1.1.1 x EF 1.1.2 X EF 1.1.3

N° OF LEVELS	EF 1.1.1	ASSIGNED
1	1	
2	3	3
3	6	
> 3	8	

N° OF UNDERGROUND LEVELS	EF 1.1.2	ASSIGNED
0	1	
1	1,1	1,1
2	1,2	

ATTIC		EF 1.1.3	ASSIGNED
NO		1	
YES	empty	1,1	
	with technical installation inside	1,2	1,2
	used as storage area	1,3	

GRADE	4,0

EF1.2 Medium Height

The Factor that considers the building's height is defined on the basis of the following parameter:

$$H_M = \frac{\sum_{i=1}^{n} \alpha_{pi} A_i H_i}{\sum_{i=1}^{n} A_i} \tag{A.2}$$

where:

- $A_i = EF1.2.1$ is the Sub-Factor dealing with the partial surface of the building's area with H_i height;
- $H_i = EF1.2.2$ is the Sub-Factor considering the partial height of the building's area with A_i surface;
- $\alpha_{pi} = EF1.2.3$ is the Sub-Factor considering if the i area with H_i height and A_i surface is opened to the public;
- n is the number of areas with H_i height and A_i surface individuated in the building.

Height H_i is always calculated under the eaves. By means of the intermediate parameter H_M, height of the different parts of the building is weighted with the surface of that area.

EF 1.2 MEDIUM HEIGHT

				EF 1.2.3		
				open to the public	partially open to the public	not open to the public
Hi = EF 1.2.1	m	Ai = EF 1.2.2	m²	1,3	1,1	1
H1	4,95	A1	1630		1,1	
H2	11	A2	1330			1
H3	10	A3	2000		1,1	
H…	6	A4	300		1,1	
Hn	0	A5	500	1,3		

H_M= 8,24 m

					EF1.2	ASSIGNED
3	≥	H_M			0	
3	<	H_M	≤	5	3	
5	<	H_M	≤	10	4	4
10	<	H_M	≤	15	6	
15	<	H_M	≤	22	7	
22	>	H_M			9	

GRADE	4

EF2.1 Stairs

The Factor that consider the presence and the number of stairs in the building is defined as follow:

$$EF2.1 = 3 + \lambda\Delta S + (1-\lambda)S_R \tag{A.3}$$

where:

$$S_R = \frac{D_s}{E_{ts}} \tag{A.4}$$

$$\Delta S = D_s - E_{ts} \tag{A.5}$$

and

$\lambda = 0,6$ is the importance of the parameter ΔS respect to the parameter S_R.

We further define:

- $D_s = EF2.1.1$ is the Sub-Factor dealing with the desired number of stairs according to the codes. It represents the code's prescription, it is the number of stairs that the building needs if the fire code is applied with no law dispensation.;
- $E_{ts} = E_{ss} + E_{es}$ is the Sub-Factor considering the total number of egress stairs present in the building;
- $E_{ss} = EF2.1.2$ is the parameter considering the total number of "safe" egress stairs present in the building. A stair is considered "safe" when has the characteristics that the fire code requests;
- $E_{es} = EF2.1.3$ is the Sub-Factor considering the total number of "equivalent safe" egress stairs present in the building. A stair is considered "equivalent safe" when it has not the characteristics that the fire code requests but it can be used as egress stairs because of the special situation in the historical building;
- $E_{tot} = E_{ts} + E_{us}$ is the parameter considering the total number of stairs present in the building, both unsafe, safe and used as egress stairs;
- E_{us} is the number of unsafe stairs present in the building. A stair is considered "unsafe" when it is not possible at all to use it as an egress stair.

EF 2.1 **STAIRS**

total n° existing stairs	4	E_{tot}
safe egress stairs (according to law)	2	E_{SS} = EF2.1.2
equivalent safe egress stairs	0	E_{ES} = EF2.1.3
total number of egress stairs	2	E_{TS}
others (unsafe stairs)	2	E_{US}
ideal number of emergency stairs	3	D_S= EF2.1.1

$S_R = D_s / E_{ss} =$	1,50
$\Delta S = D_s - E_{ss} =$	1
$SF = 3 + (\lambda\, \Delta S + (1-\lambda)\, S_R) =$	4,2
λ =	0,60
GRADE	4,2

EF2.2 Vertical Connections

This Factor considers the presence of vertical connections among the floors, due to architectonical features. The presence of salons, theatres, halls can create obstacles in evacuation both of people and Valuable Contents and it is a critical point in fire spread. This Factor is composed by two Sub-Factors:

- $EF2.2.1$ is a Sub-Factor that considers the possible presence of double heights in the building;
- $EF2.2.2$ is a Sub-Factor that considers the possible presence spread flues and chimneys in the building.

$EF2.2.1$ acts in all the Objectives (ref. paragraph 5.1.4) while $EF2.2.2$ has to be considered only with respect to the *Objective 3: Fire and smoke spread.*

EF 2.2 DOUBLE HEIGHTS

	EF 2.2.1	ASSIGNED
NO	0	
1 DOUBLE HEIGHT: 2 levels HEIGTH	5	5
1 DOUBLE HEIGHT: 3 levels HEIGTH	7	
> 1 DOUBLE HEIGHT	9	
GRADE	5	

Amplification due to flues and chimneys	EF 2.2.2	Assigned
No flues and chimneys	1	1
Spread flues and chimneys directly det	1,2	
Possible presence of ancient flues and	1,3	

EF3.1 Fire brigade response time

In this Factor the fire brigade response time is considered. In some special case, we have on site fireman inside Historical Heritage Buildings (these cases have to be discussed on the base of the regulations; i.e. public shows inside historical building). The time required for a suitably equipped fire brigade team to reach the site of the fire is essential in terms of limiting the extent of fire and the damage. Response time is strictly linked to the distance between fire station and building and probability of traffic jam has to be included in the evaluation. It is assumed that fire brigade equipment is adapted to the task they may have to fulfill.

EF 3.1 FIRE BRIGADE RESPONSE TIME

RESPONSE TIME	EF 3.1.1	ASSIGNED
0-5 min (on site fireman)	2	
5-10 min	4	
10-15 min	6	6
> 15 min	8	

GRADE	6

The permanent presence of trained staff facilitates and accelerates the first intervention on a starting fire and can this way limit the extent of damage. If from the calculation comes a $FireServiceIndex \leq 2$ it is possible to take a step up with respect to the real situation in the upper table. Building's manager can take special agreements with the fire brigades to reduce their intervention time.

EF3.2 Surroundings

Surroundings of the analysed building are here checked. $EF3.2$ factor is defined as follow:

$$EF3.2 = EF3.2.3 \times I_D \tag{A.6}$$

where:

- $EF3.2.3$ is a Sub-Factor considering the position of the building with respect to the urban configuration of the city;
- I_D is a parameter composed by Sub-Factor $EF3.2.1$ and $EF3.2.2$.

I_D is defined as follow:

$$I_D = \frac{\sum_{i=1}^{n}(\lambda G_i + (1-\lambda)A_i)}{n} \tag{A.7}$$

where:

- n is the number of building's sides;
- λ=0,5 is the importance of the parameter G_i with respect to the parameter A_i;
- $G_i = EF3.2.1$ is the Sub-Factor that takes into account the distance between the analysed side and opposite buildings;
- $A_i = EF3.2.2$ is the Sub-Factor that takes into account the accessibility of the analysed side.

$EF3.2.1$ and $EF3.2.2$ are attributed for each side of the building.

EF 3.2 **SURROUNDINGS**

EF building are separated by a firewall this is deemed to be equivalent to 8m distance

EF3.2= EF3.2.3 x ID

Distance between (adjacent) buildings $I_D = \Sigma_i^n \lambda G_i + (1-\lambda)Ai / n =$ 6,125

Number of sides/facades of the building n= 4

Importance of G_i respect to A_i λ= 0,5

	Distance between facade and opposite buildings	Accessibility of each side	Not accessible	less than 1 window for each level accessible	1 window for each level accessible	More than 1 window for each level accessible	All windows for each level accessible	
SIDE	Gi= EF3.2.1	Ai= EF3.2.2	9	7	6	5	4	ASSIGNED I_D
SIDE1	D < 3,5m - not accessible for the fire	9	9,00	9,00	9,00	9,00	9,00	4,50
	3,5 ≤ D ≤ 6m	7	8,00	7,00	6,50	6,00	5,50	
	6 < D ≤ 9m	5	7,00	6,00	5,50	5,00	4,50	
	9 < D ≤ 20m	3	6,00	5,00	4,50	4,00	3,50	
	20m > D	1	5,00	4,00	3,50	3,00	2,50	
SIDE2	D < 3,5m	9	9,00	9,00	9,00	9,00	9,00	5,00
	3,5 ≤ D ≤ 6m	7	8,00	7,00	6,50	6,00	5,50	
	6 < D ≤ 9m	5	7,00	6,00	5,50	5,00	4,50	
	9 < D ≤ 20m	3	6,00	5,00	4,50	4,00	3,50	
	20m > D	1	5,00	4,00	3,50	3,00	2,50	
SIDE …	D < 3,5m	9	9,00	9,00	9,00	9,00	9,00	9,00
	3,5 ≤ D ≤ 6m	7	8,00	7,00	6,50	6,00	5,50	
	6 < D ≤ 9m	5	7,00	6,00	5,50	5,00	4,50	
	9 < D ≤ 20m	3	6,00	5,00	4,50	4,00	3,50	
	20m > D	1	5,00	4,00	3,50	3,00	2,50	
SIDE n	D < 3,5m	9	9,00	9,00	9,00	9,00	9,00	6,00
	3,5 ≤ D ≤ 6m	7	8,00	7,00	6,50	6,00	5,50	
	6 < D ≤ 9m	5	7,00	6,00	5,50	5,00	4,50	
	9 < D ≤ 20m	3	6,00	5,00	4,50	4,00	3,50	
	20m > D	1	5,00	4,00	3,50	3,00	2,50	

URBAN LOCATION	EF 3.2.3	ASSIGNED
IN HISTORICAL CENTRE and TRAFFIC RESTRICTED AREA	1,4	
IN HISTORICAL CENTRE	1,2	
OUTSIDE HISTORICAL CENTRE	1	1

GRADE	6,13

IF1.1 Smoke control system

In cultural heritage buildings, smoke control:

- contributes to the safe evacuation of people between substantial times;
- limits the smoke damage to cultural heritage content.

The grade of implementation has to be evaluated regarding the efficiency of prohibiting smoke to spread beyond the room of origin of the fire during its expected duration. The efficiency of smoke control systems depends upon the activation of the smoke control system (manual versus automatic) and the type of system:

- natural ventilation through openings;
- mechanical ventilation;
- pressurisation and ventilation (natural, mechanical or mixed) for smoke.

$IF1.1$ factor is defined as follow:

$$IF1.1 = IF1.1.1 \times IF1.1.2 \tag{A.8}$$

where:

- $IF1.1.1$ is a Sub-Factor considering the characteristics of the smoke control system;
- $IF1.1.2$ is a Sub-Factor considering the maintenance of the smoke control system.

IF 1.1 SMOKE CONTROL SYSTEM

IF1.1 = IF 1.1.1 x IF 1.1.2

		Activation of smoke control system = IF 1.1.1			ASSIGNED
		Automatically	Manually	No smoke control system	
Type of smoke control	Natural ventilation through openings near ceiling	2	6	7	1
	Mechanical ventilation	2	6	7	
	Pressurisation and natural or mechanical or mixed ventilation for exiting smoke	1	4	7	

MAINTENANCE	IF 1.1.2	ASSIGNED
once a years	1,5	
twice a year	1	1

GRADE	7

IF1.2 Detection system

This Factor is evaluated on the basis of the distribution and the type of detectors. $IF1.2$ factor is defined as follow:

$$IF1.2 = IF1.2.3 \times I_{DET} \tag{A.9}$$

where:

- $IF1.2.3$ is a Sub-Factor considering the maintenance of the detection system;
- I_{DET} is a parameter composed by Sub-Factor $IF1.2.1$ and $IF1.2.2$.

I_{DET} is defined as follow:

$$I_{DET} = \lambda D_{Ds} + (1 - \lambda) T_{Ds} \tag{A.10}$$

where:

- λ=0,5 is the importance of the parameter D_{Ds} with respect to the parameter T_{Ds};
- $D_{Ds} = IF1.2.1$ is the Sub-Factor that takes into account the distribution of the system in the sector;
- $T_{Ds} = IF1.2.2$ is the Sub-Factor that takes into account the type of system.

If in the sector there are Laser Detection System or Air Sampling Detection System, risk index for $IF1.2$ is **1**.
If there is no detection system nor in the rooms or in the escape routes, risk index for $IF1.2$ is 9.

IF 1.2 DETECTION SYSTEM

IF 1.2 = IF 1.2.3 x I_{DET}

I_{DET}= λ Ds + (1-λ) Ty = 3,00
λ = 0,50

Ds= Distribution of detectors			IF 1.2.2 = Ty = Type of detector								
			Heat detectors		Smoke detectors		Heat and smoke detectors with CPU on board		NOT DEPENDENT ON THE NUMBER OF DETECTORS	Laser detection System or Air sampling detection system	ASSIGNED
			Wireless	Wired	Wireless	Wired	Wireless	Wired			
Detectors in rooms/compartments	Detectors in the escape route		6	5	5	4	3	2		1	
None in the rooms	NO	9	9,0	9,0	9,0	9,0	9,0	9,0		1	3
	YES	6	6,0	5,5	5,5	5,0	4,5	4,0		1	
At least one in every room	NO	6	6,0	5,5	5,5	5,0	4,5	4,0		1	
	YES	4	5,0	4,5	4,5	4,0	3,5	3,0		1	
More than one in every room	NO	2	4,0	3,5	3,5	3,0	2,5	2,0		1	
	YES	1	3,5	3,0	3,0	2,5	2,0	1,5		1	

MAINTENANCE	IF 1.2.3	ASSIGNED
once a years	1,5	
twice a year	1	1

GRADE	3

IF1.3 Suppression system

Both automatic and portable fire suppression means are covered by this Factor. Ultimately the efficiency of both aspects has to be evaluated on the basis of their capacity to extinguish a starting fire. For automatic fire suppression systems the type and the location of heads are important.

The efficiency of portable extinguishers depends entirely on the presence of trained people; one of the duties of the building's manager is to make the staff trained.
$IF1.3$ factor is defined as follow:

$$IF1.3 = IF1.3.4 \times I_{SUPP} \tag{A.11}$$

where:

- $IF1.3.4$ is a Sub-Factor considering the maintenance of the suppression system;
- I_{SUPP} is a parameter composed by Sub-Factor $IF1.3.1$, $IF1.3.2$ and $IF1.3.3$.

I_{SUPP} is defined as follow:

$$I_{SUPP} = \lambda A_s + \alpha_T(1 - \lambda)P_{eq} \tag{A.12}$$

where:

- λ is the importance of the parameter A_s respect to the parameter P_{eq} and it depends on the type and location of the system;
- $A_s = IF1.3.1$ is the Sub-Factor that takes into account the type and the location of the automatic system in the sector;
- $P_{eq} = IF1.3.2$ is the Sub-Factor that takes into account the portable equipment for fire suppression present in the sector.
- $\alpha_T = IF1.3.3$ is the Sub-Factor that takes into account the reliability of Fire Service Team.

Among the assigned indexes in the table, the maximum grade is chosen to be assigned to the sector.

IF 1.3 **SUPPRESSION SYSTEM**

GRADE = IF 1.3.4 x I_{SUPP}

$I_{SUPP}=\lambda\ As + \alpha_T\ (1-\lambda)\ Peq =$

α_T = 1if nor automatic system or portable equipment is available

Automatic system: Location	Type	λ		Portable equipment: None	Extinguishing eq. NOT in every	Extinguishing eq. in every room	ASSIGNED
				7	5	3	
in rooms/compartments with highest fire load	No automatic system	0	7	5,6	3,2	1,9	3,20
	Sprinkler	0,50	5	4,2	3,6	3,0	
	Gas system	0,35	4	4,0	3,2	2,4	
	Special system (i.e. watermist)	0,50	4	3,8	3,2	2,6	
in rooms/compartments with valuable contents	No automatic system	0	7	5,6	3,2	1,9	4,17
	Sprinkler	0,40	8	5,2	4,5	3,7	
	Gas system	0,65	3	3,1	2,7	2,2	
	Special system (i.e. watermist)	0,65	5	4,2	3,7	3,3	
in the remaining parts of the analysed sector	No automatic system	0	7	5,6	3,2	1,9	2,16
	Sprinkler	0,50	8	5,4	4,8	4,2	
	Gas system	0,50	4	3,8	3,2	2,6	
	Special system (i.e. watermist)	0,50	3	3,4	2,8	2,2	

RELIABILITY OF FIRE PROTECTION TEAM	IF 1.3.3	ASSIGNED
FSI≤ 2 EXCELLENT	0,8	0,8
2<FSI≤3 VERY GOOD	1,2	
3<FSI≤4 LAW MINIMUM COMPLIANCE	1,5	
4<FSI NOT ACCEPTABLE	2	

AUTOMATIC and PORTABLE SYSTEM MAINTENANCE	IF 1.3.4	ASSIGNED
once a years	1,2	0,8
twice a year	1	
Fire protection team audit	0,8	

GRADE	4,17

IF1.4 Alarm system

Emergency and alarm signs start the evacuation of occupants and in this way intervene mainly for the safety of people. They also contribute to more immediate salvage intervention of contents. Their efficiency is a function of the type, number and location of the signals. If the detection signal is directly (automatically) sent to a central dispatching centre (e.g. fire brigade or other), the rescue process can start earlier. Duty of the building's manager is to organize the rescue team taking agreement with fire brigade or private surveillance company. $IF1.4$ factor is defined as follow:

$$IF1.4 = IF1.4.3 \times I_{AL} \tag{A.13}$$

where:

- $IF1.4.3$ is a Sub-Factor considering the maintenance of the alarm system;
- I_{AL} is a parameter composed by Sub-Factor $IF1.4.1$ and $IF1.4.2$.

I_{AL} is defined as follow:

$$I_{AL} = \lambda T_{al} + (1-\lambda) L_{al} \tag{A.14}$$

where:

- λ =0,4 is the importance of the parameter T_{al} with respect to the parameter L_{al};

- $T_{al} = IF1.4.1$ is the Sub-Factor that takes into account the type of the alarm system in the sector;
- $L_{al} = IF1.4.2$ is the Sub-Factor that takes into account the location of the alarm system.

IF 1.4 ALARM SYSTEM

GRADE =	IF 1.4.3 I_{AL}
$I_{Al} = \lambda$ Tal + (1-λ) Lal =	3,40
λ =	0,4

Type			Location	
			signal only in the room/compartment	signal sent manually at the whole building
sound signal	light signal		4	3
No	N	9	9	9
	Y	8	5,6	5,0
Alarm bell	N	4	4,0	3,4
	Y	4	4,0	3,4
Spoken signal	N	1	2,8	2,2
	Y	1	2,8	2,2

MAINTENANCE	IF1.4.3	ASSIGNED
once a years	1,5	1
twice a year	1	

GRADE	3,4

IF2.1 Type of evacuation routes
Stairs, windows and balcony can be considered as evacuation routes. Since stairs lead people through internal evacuation routes and windows and balcony lead mainly contents to fire brigade rescue, two different categories are created: (i) internal connections and (ii) external evacuation routes. $IF2.1$ factor is defined as follow:

$$IF2.1 = IF2.1.3 \times I_{TY} \tag{A.15}$$

where:

- $IF2.1.3$ is a Sub-Factor considering if the escape route functions as an escape route for Valuable Contents;
- I_{TY} is a parameter composed by Sub-Factor $IF2.1.1$ and $IF2.1.2$.

I_{TY} is defined as follow:

$$I_{TY} = \lambda E_{ext} + (1 - \lambda) E_{int} \tag{A.16}$$

where:

- λ =0,3 is the importance of the parameter T_{al} respect to the parameter L_{al};
- $E_{ext} = IF2.1.1$ is the Sub-Factor that takes into account the type of external evacuation routes in the sector;
- $E_{int} = IF2.1.2$ is the Sub-Factor that takes into account the type of internal evacuation routes in the sector.

If more than a combination of the Sub-Factors is suitable to the sector, the worst grade is assigned.

IF 2.1 TYPE OF EVACUATION ROUTES

GRADE = IF2.1.3 I_{TYPE}

λ= 0,3 $I_{TYPE} = \lambda I_{EXT} + (1-\lambda)\, I_{INT}$

						Staircases and internal connections				
						One staircase may be used as an evacuation route	Escape route leading to two independent staircases	Direct escape to two independent staircases	Direct communication with at least one safe fire compartment at the same floor	
		Number	Dimensions and characteristics			7	5	4	3	Assigned
External evacuation routes: Window/balcony	Windows and balcony cannot be used as evacuation route	-	-		9	7,6	6,2	5,5	4,8	
	windows	1	NOT at ground floor		7	7,0	5,6	4,9	4,2	
			at ground floor		5	6,4	5,0	4,3	3,6	
		> 1	NOT at ground floor		5	6,4	5,0	4,3	3,6	
			at ground floor		2	5,5	4,1	3,4	2,7	2,7
	balcony	1	surface ≥ 3,5m x 3,5m	reachable with a permanent stair	3	5,8	4,4	3,7	3,0	
				reachable with a Fire Brigade Ladder	4	6,1	4,7	4,0	3,3	
			surface < 3,5m x 3,5m	reachable with a permanent stair	5	6,4	5,0	4,3	3,6	
				reachable with a Fire Brigade Ladder	6	6,7	5,3	4,6	3,9	
		> 1	surface ≥ 3,5m x 3,5m	reachable with a permanent stair	2	5,5	4,1	3,4	2,7	
				reachable with a Fire Brigade Ladder	3	5,8	4,4	3,7	3,0	
			surface < 3,5m x 3,5m	reachable with a permanent stair	4	6,1	4,7	4,0	3,3	
				reachable with a Fire Brigade Ladder	5	6,4	5,0	4,3	3,6	

Importance of the work of art to be evacuated	IF 2.1.3	ASSIGNED
Unclassified: items that will be left in place	1	
Third Priority: items that would be difficult or expensive to replace and which contribute to the history of the building	1,1	
Second priority: items of national value or which are important to explain the history of the building or its occupants. This should also include items that have a high monetary value	1,3	
First priority: items of international heritage value which are intimately connected with the building or its previous occupants	1,5	1,5
	GRADE	4,05

IF2.2 Dimensions and layout

In this Factor the following parameters are considered:

- $D = IF2.2.1$ that is the maximum travel distance to reach a safe place according to italian law DM 10/03/1998;
- $NF = IF2.2.2$ that is the number of floors to walk;
- $NS = IF2.2.3$ that is the number of sectors connected to the escape route.

Limits for walking distance are chosen according to italian law DM 10/03/1998 [9]; maximum number of floors to walk (up or down) is chosen according to Table 5.10. If the vertical connection is protected, it could be an advantage to have a big number of sector connected. On the contrary, if the vertical connection is not protected the more are the connected sectors the worst is the situation.

IF 2.2 **DIMENSIONS AND LAYOUT**

IF 2.2.1	IF 2.2.2	IF 2.2.3			
Maximum travel distance	Number of floors to go walk	Number of sectors connected to the escape route			
		not protected stair		protected stair	
		NS > 4	NS ≤ 4	NS > 4	NS ≤ 4
D ≥ 30m	NF >3	9,0	7,0	3,0	3,0
	NF ≤ 3	5,5	5,5	1,0	2,0
15m ≤ D <30 m	NF >3	3,6	3,6	3,0	3,0
	NF ≤ 3	2,0	2,0	1,0	2,0
D < 15m	NF >3	2,0	2,0	2,0	2,0
	NF ≤ 3	1,0	1,0	1,0	1,0

GRADE	1,0

IF2.3 Linings and floorings

Reaction to fire is evaluated against the probability that flash-over may occur in critical spaces as escape routes. The grade for this Sub-Factor can be attributed on basis of the reaction to fire class of large surfaces, i.e. walls and ceiling linings. The worst class product occupying over 20% of the walls, or 20% of the ceiling is considered dominant for the attribution of the grade. The grade is linked with the potential contribution of the product to flash-over in an escape route and it is linked to product's Euroclass classification.

IF 2.3 LININGS AND FLOORINGS

	Type (EUROCLASS CLASSIFICATION)		ASSIGNED
No flash-over	Stone, concrete, gypsum boards (A1-A2)	2	2
No or limited contribution to flash-over	Best FR woods impregnated, thick gypsum boards (B)	4	
No flash-over within 10min	Textile wall cover on gypsum board (C)	5,5	
Flash-over within 10min	Wood untreated (D)	7	
Flash over with two minutes	Some plastics (E/F)	9	

GRADE	2,0

IF3.1 Vertical Structure
Vertical Structure is the structure composing the walls or columns of the analysed sector. The grade is linked with the resistance capacity that materials can assure. The worst type of structure occupying over 20% of the total is considered dominant for the attribution of the grade.

IF 3.1 VERTICAL STRUCTURE

Is it to assign the index belonging to the worst class covering ≥20% of the tot

	SURFACE % ESTIMATION	IF3.1.1	ASSIGNED
STONE; CONCRETE	75%	3	3
WOOD	15%	8	
STEEL	6%	7	
PROTECTED WOOD	4%	3	
PROTECTED STEEL	0%	3	
	100%		

GRADE	3

IF3.2 Horizontal Structure
Horizontal Structure is the structure composing the floors you walk on in the sector. The grade, as for Factor $IF3.1$, is linked with the resistance capacity that materials can assure. The worst type of structure occupying over 20% of the total surface is considered dominant for the attribution of the grade.

IF 3.2 HORIZONTAL STRUCTURE

Is it to assign the index belonging to the worst class covering ≥20% of the tot

	SURFACE % ESTIMATION	IF3.1.1	ASSIGNED
STONE; CONCRETE	40%	3	3
WOOD	60%	7	
STEEL	0%	7	
PROTECTED WOOD	0%	3	
PROTECTED STEEL	0%	3	
	100%		

GRADE	3

Appendix B

Sensitivity Analysis

This annex provides full results from sensitivity analysis performed on the definitive AHP structure. Sensitivity analysis has been conducted for:

- each set of Factors with respect to the corresponding Characteristic and each Objective (sensitivity analysis of level 4 with respect to level 3 of the hierarchical structure);
- each set of Characteristics with respect to each Objective (sensitivity analysis of level 3 with respect to level 2 of the hierarchical structure).

For each set of parameters Tornado Diagrams and Spider Charts are here plotted together with the corresponding data coming out from the spreadsheets.

B.1 Sensitivity analysis of level 4 with respect to level 3 - Factors vs Characteristics

B.1.1 External Analysis

B.1.1.1 EC1 vs OB1

Figures B.1 and B.2 show sensitivity analysis of EC1 with respect to OB1.

Input Variable	Corresponding Input Value: Low Output	Base Case	High Output	EC1 Output Value: Low	Base	High	Swing	Percent Swing^2
EF1.1	1	5,5	12,48	2,8	5,5	9,688	6,888	78,5%
EF1.2	0	5,5	9	3,3	5,5	6,9	3,6	21,5%

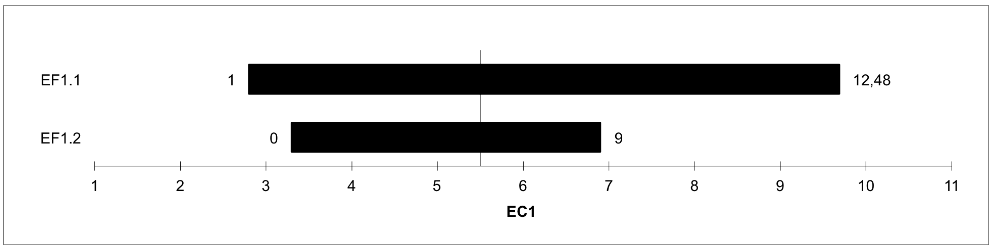


Figure B.1: Sensitivity analysis of EC1 with respect to OB1: tornado diagram.

Input Variable	Corresponding Input Value: Low Output	Base Case	High Output	Input Value as % of Base: Low %	Base %	High %	EC1 Output Value: Low	Base	High	Swing
EF1.1	1	5,5	12,48	18,2%	100,0%	226,9%	2,8	5,5	9,688	6,888
EF1.2	0	5,5	9	0,0%	100,0%	163,6%	3,3	5,5	6,9	3,6

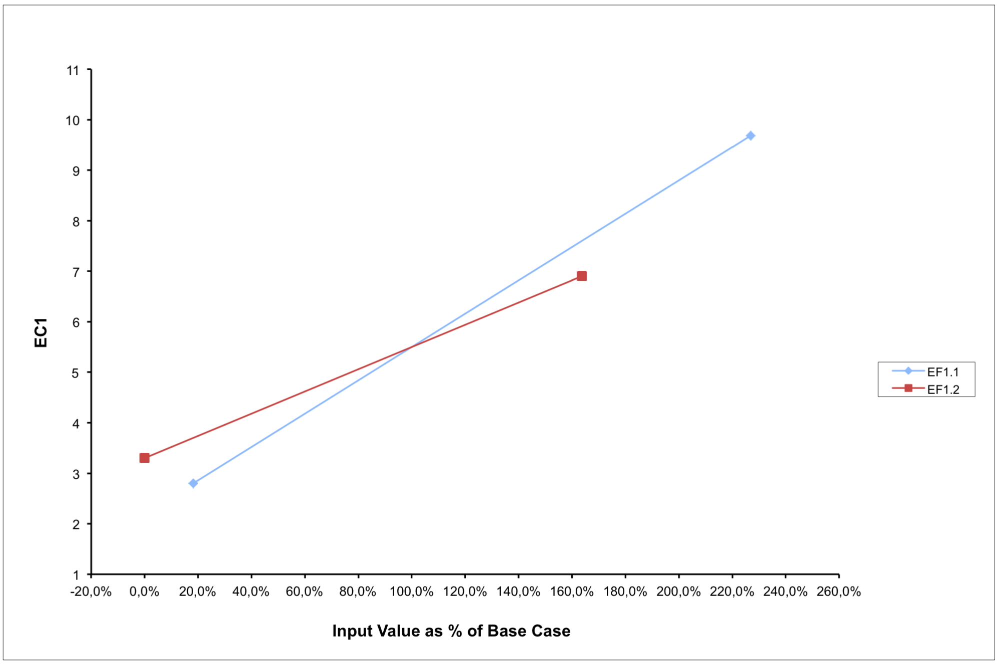


Figure B.2: Sensitivity analysis of EC1 with respect to OB1: spider chart.

B.1.1.2 EC1 vs OB2

Figures B.3 and B.4 show sensitivity analysis of EC1 with respect to OB2.

	Corresponding Input Value			EC1 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
EF1.1	1	5,5	12,48	2,35	5,5	10,386	8,036	89,9%
EF1.2	0	5,5	9	3,85	5,5	6,55	2,7	10,1%

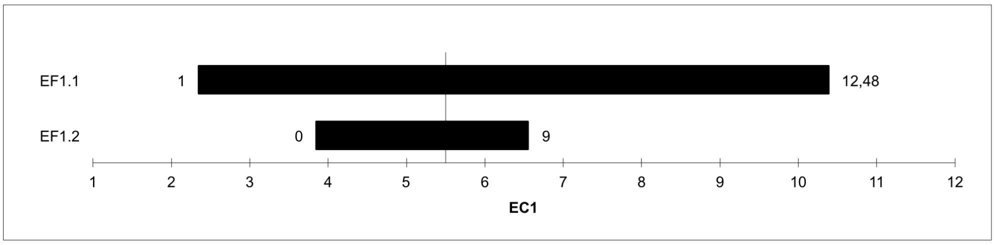


Figure B.3: Sensitivity analysis of EC1 with respect to OB2: tornado diagram.

	Corresponding Input Value			Input Value as % of Base			EC1 Output Value			
Input Variable	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	Swing
EF1.1	1	5,5	12,48	18,2%	100,0%	226,9%	2,35	5,5	10,386	8,036
EF1.2	0	5,5	9	0,0%	100,0%	163,6%	3,85	5,5	6,55	2,7

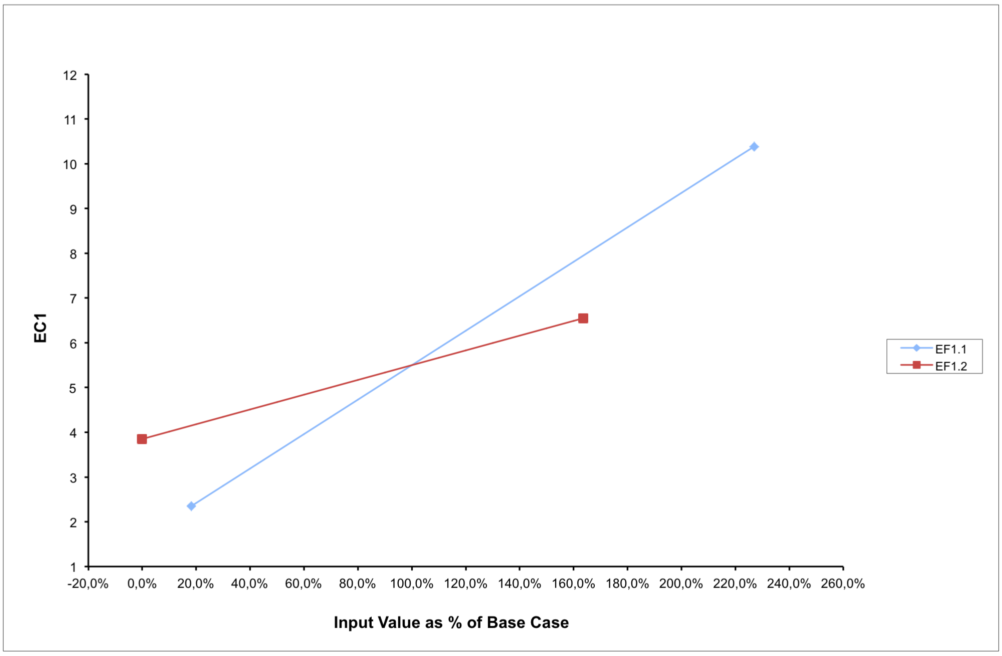


Figure B.4: Sensitivity analysis of EC1 with respect to OB2: spider chart.

B.1.1.3 EC1 vs OB3

Figures B.5 and B.6 show sensitivity analysis of EC1 with respect to OB3.

	Corresponding Input Value			EC1 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
EF1.2	0	5,5	9	1,1	5,5	8,3	7,2	90,8%
EF1.1	1	5,5	12,48	4,6	5,5	6,896	2,296	9,2%

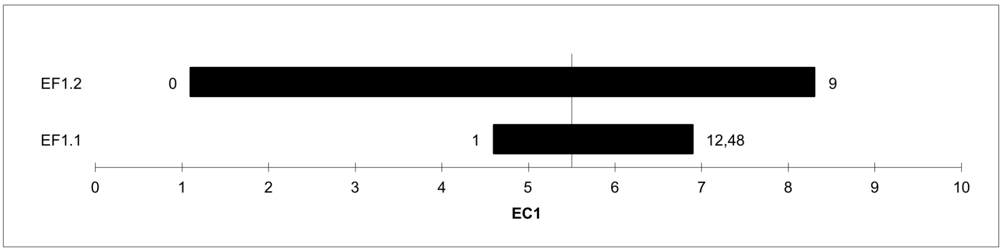


Figure B.5: Sensitivity analysis of EC1 with respect to OB3: tornado diagram.

	Corresponding Input Value			Input Value as % of Base			EC1 Output Value			
Input Variable	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	Swing
EF1.2	0	5,5	9	0,0%	100,0%	163,6%	1,1	5,5	8,3	7,2
EF1.1	1	5,5	12,48	18,2%	100,0%	226,9%	4,6	5,5	6,896	2,296

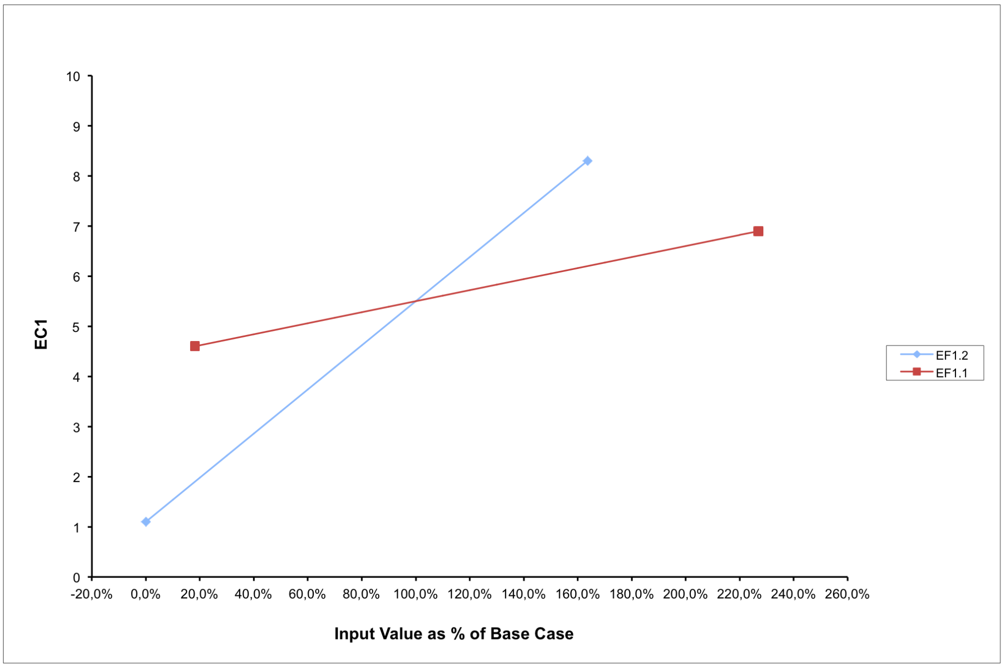


Figure B.6: Sensitivity analysis of EC1 with respect to OB3: spider chart.

B.1.1.4 EC2 vs OB1

Figures B.7 and B.8 show sensitivity analysis of EC2 with respect to OB1.

	Corresponding Input Value			EC2 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
EF2.1	1	4	9	1,6	4,15	8,4	6,8	96,2%
EF2.2	0	5	9	3,4	4,15	4,75	1,35	3,8%

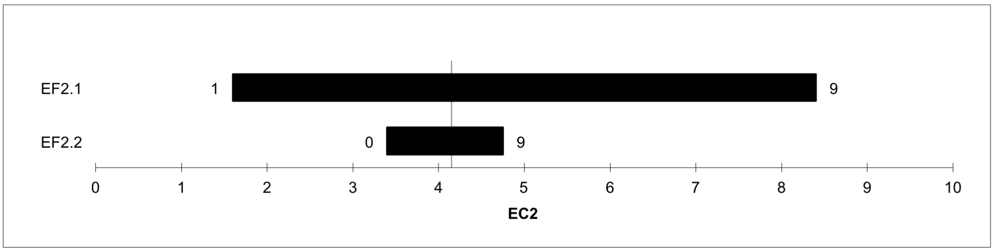


Figure B.7: Sensitivity analysis of EC1 with respect to OB1: tornado diagram.

	Corresponding Input Value			Input Value as % of Base			EC2 Output Value			
Input Variable	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	Swing
EF2.1	1	4	9	25,0%	100,0%	225,0%	1,6	4,15	8,4	6,8
EF2.2	0	5	9	0,0%	100,0%	180,0%	3,4	4,15	4,75	1,35

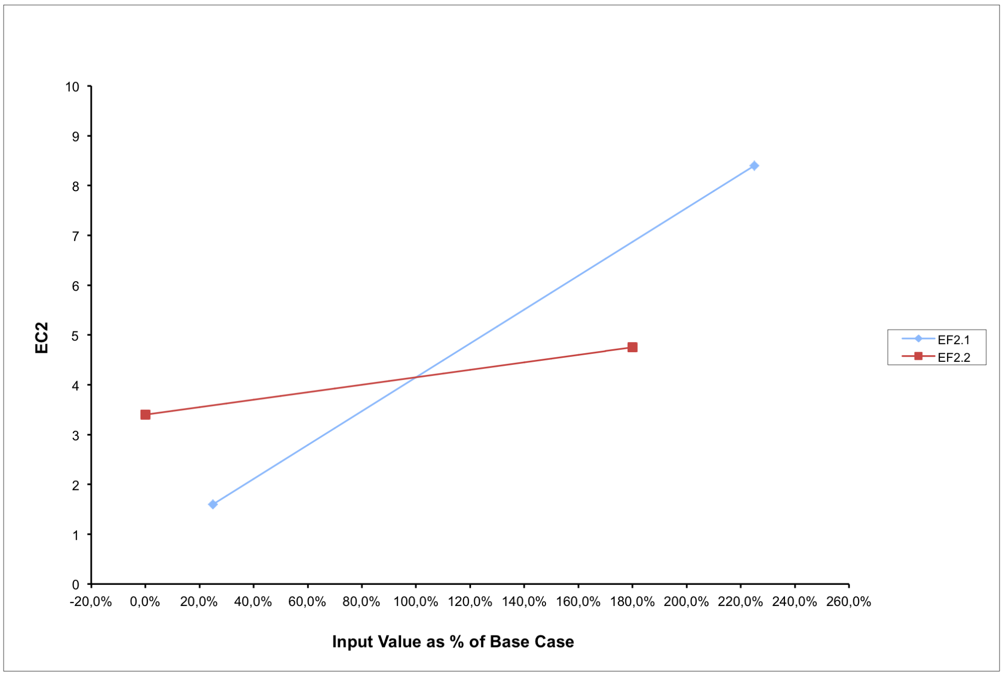


Figure B.8: Sensitivity analysis of EC2 with respect to OB1: spider chart.

B.1.1.5 EC2 vs OB2

Figures B.9 and B.10 show sensitivity analysis of EC2 with respect to OB2.

	Corresponding Input Value			EC2 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
EF2.1	1	4	9	2,4	4,35	7,6	5,2	73,2%
EF2.2	0	5	9	2,6	4,35	5,75	3,15	26,8%

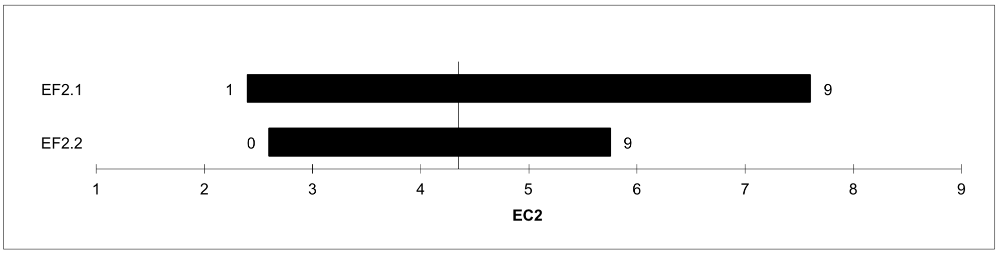


Figure B.9: Sensitivity analysis of EC2 with respect to OB2: tornado diagram.

	Corresponding Input Value			Input Value as % of Base			EC2 Output Value			
Input Variable	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	Swing
EF2.1	1	4	9	25,0%	100,0%	225,0%	2,4	4,35	7,6	5,2
EF2.2	0	5	9	0,0%	100,0%	180,0%	2,6	4,35	5,75	3,15

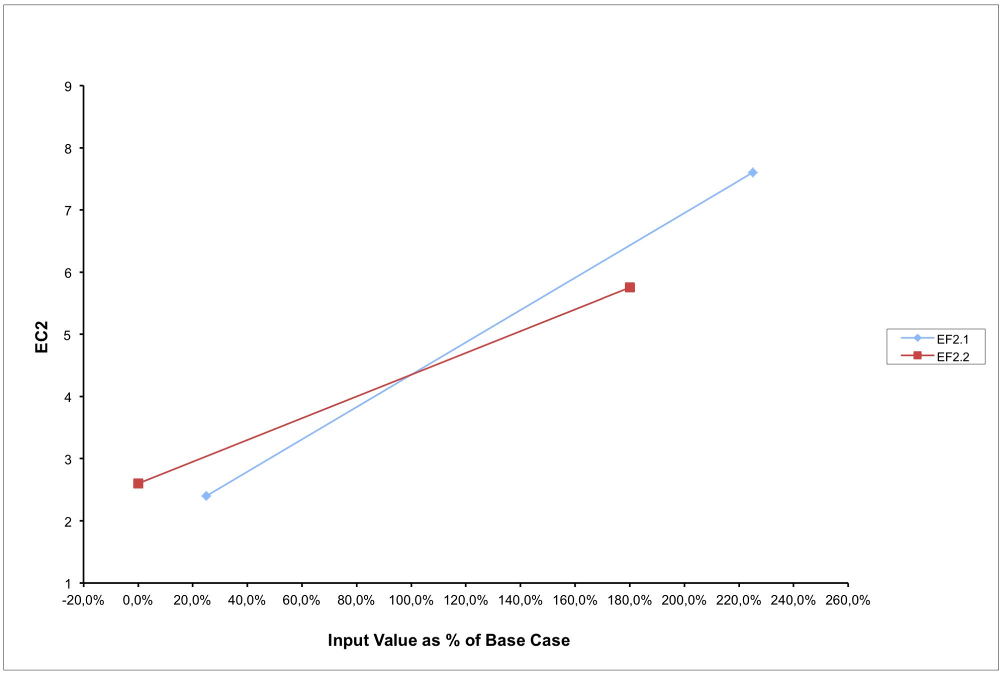


Figure B.10: Sensitivity analysis of EC2 with respect to OB2: spider chart.

B.1.1.6 EC2 vs OB3

Figures B.11 and B.12 show sensitivity analysis of EC2 with respect to OB3.

	Corresponding Input Value			EC2 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
EF2.2	0	5	9	0,8	4,8	8	7,2	95,3%
EF2.1	1	4	9	4,2	4,8	5,8	1,6	4,7%

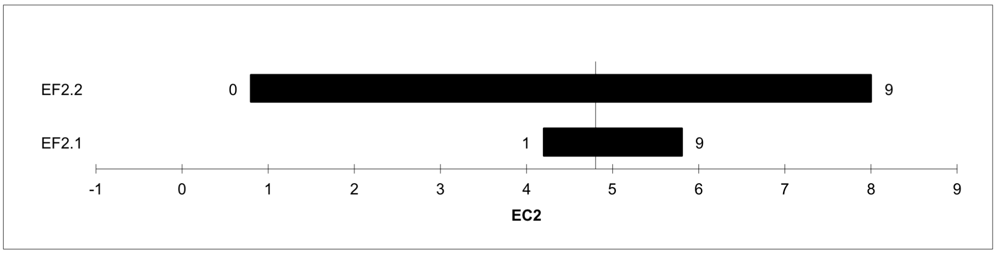


Figure B.11: Sensitivity analysis of EC2 with respect to OB3: tornado diagram.

	Corresponding Input Value			Input Value as % of Base			EC2 Output Value			
Input Variable	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	Swing
EF2.2	0	5	9	0,0%	100,0%	180,0%	0,8	4,8	8	7,2
EF2.1	1	4	9	25,0%	100,0%	225,0%	4,2	4,8	5,8	1,6

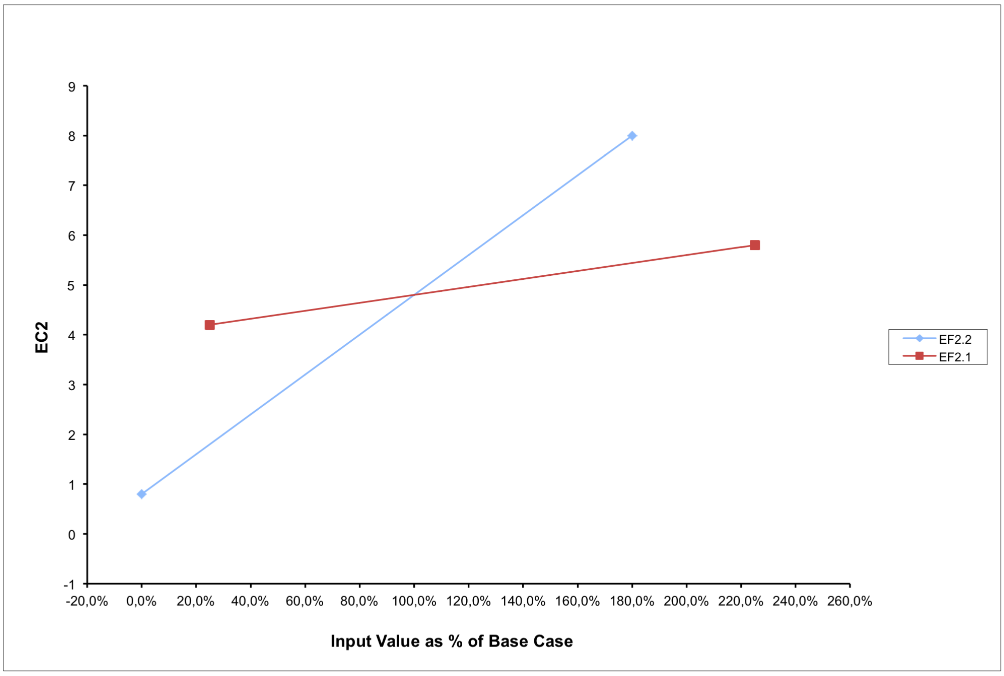


Figure B.12: Sensitivity analysis of EC2 with respect to OB3: spider chart.

B.1.1.7 EC3 vs OB1

Figures B.13 and B.14 show sensitivity analysis of EC3 with respect to OB1.

Input Variable	Corresponding Input Value: Low Output	Base Case	High Output	EC3 Output Value: Low	Base	High	Swing	Percent Swing^2
EF3.1	2	4	8	3,225	4,525	7,125	3,9	54,9%
EF3.2	2,5	5,5	12,6	3,475	4,525	7,01	3,535	45,1%

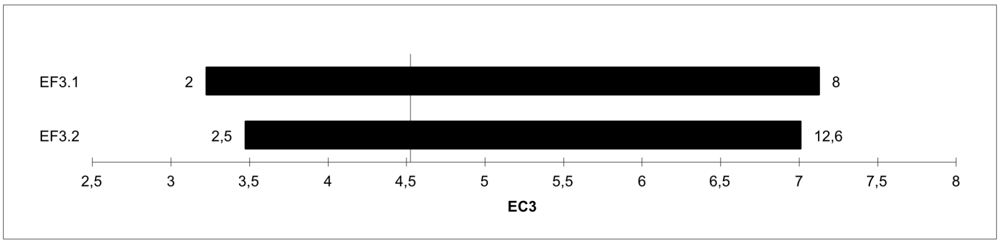


Figure B.13: Sensitivity analysis of EC3 with respect to OB1: tornado diagram.

Input Variable	Corresponding Input Value: Low Output	Base Case	High Output	Input Value as % of Base: Low %	Base %	High %	EC3 Output Value: Low	Base	High	Swing
EF3.1	2	4	8	50,0%	100,0%	200,0%	3,225	4,525	7,125	3,9
EF3.2	2,5	5,5	12,6	45,5%	100,0%	229,1%	3,475	4,525	7,01	3,535

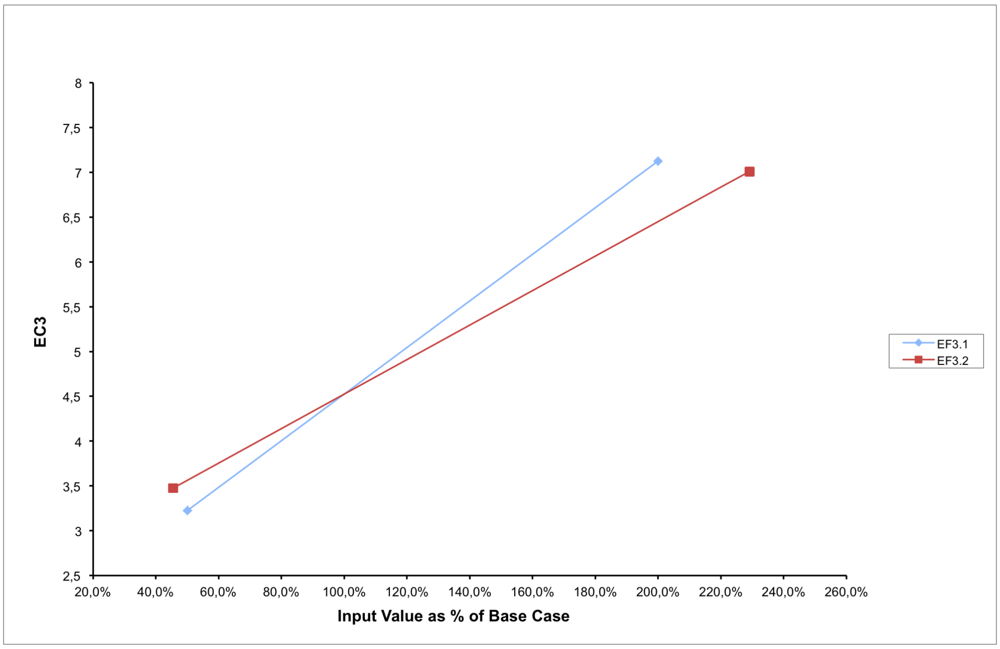


Figure B.14: Sensitivity analysis of EC3 with respect to OB1: spider chart.

B.1.1.8 EC3 vs OB2

Figures B.15 and B.16 show sensitivity analysis of EC3 with respect to OB2.

	Corresponding Input Value			EC3 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
EF3.1	2	4	8	3,225	4,525	7,125	3,9	54,9%
EF3.2	2,5	5,5	12,6	3,475	4,525	7,01	3,535	45,1%

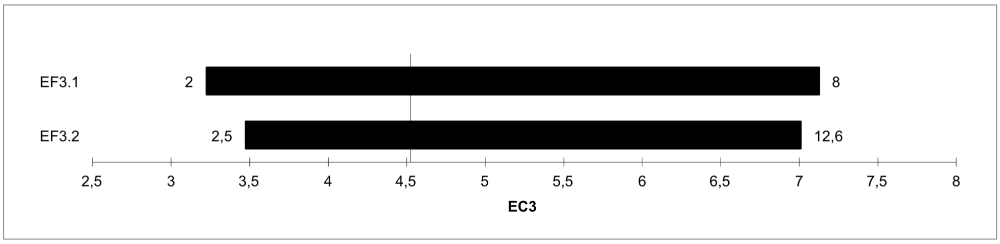


Figure B.15: Sensitivity analysis of EC3 with respect to OB2: tornado diagram.

	Corresponding Input Value			Input Value as % of Base			EC3 Output Value			
Input Variable	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	Swing
EF3.1	2	4	8	50,0%	100,0%	200,0%	3,225	4,525	7,125	3,9
EF3.2	2,5	5,5	12,6	45,5%	100,0%	229,1%	3,475	4,525	7,01	3,535

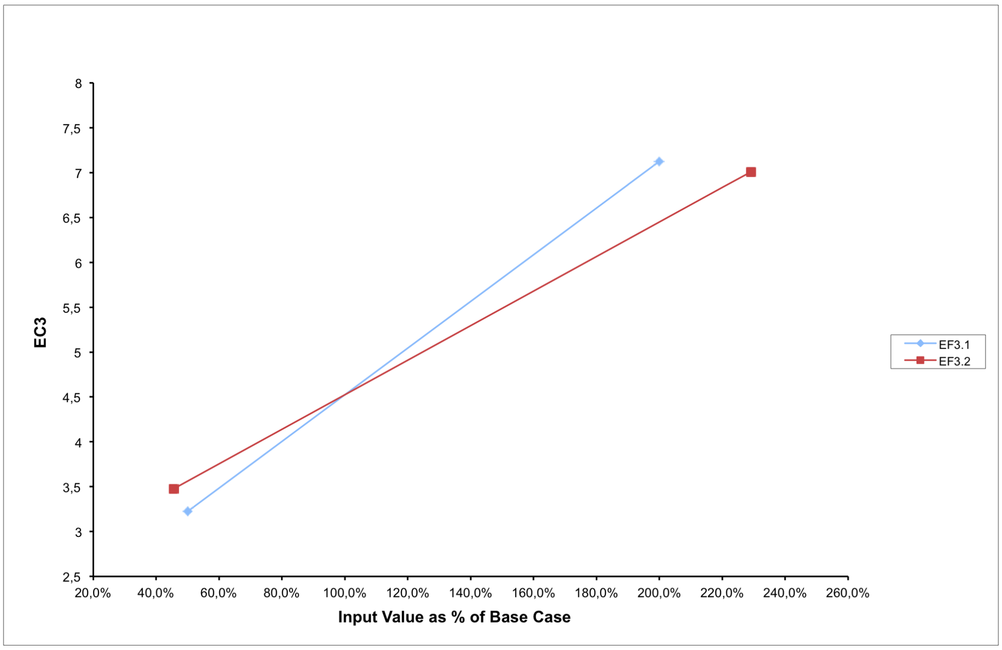


Figure B.16: Sensitivity analysis of EC2 with respect to OB2: spider chart.

B.1.1.9 EC3 vs OB3

Figures B.17 and B.18 show sensitivity analysis of EC3 with respect to OB3.

	Corresponding Input Value			EC3 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
EF3.2	2,5	5,5	12,6	3,4	4,6	7,44	4,04	55,7%
EF3.1	2	4	8	3,4	4,6	7	3,6	44,3%

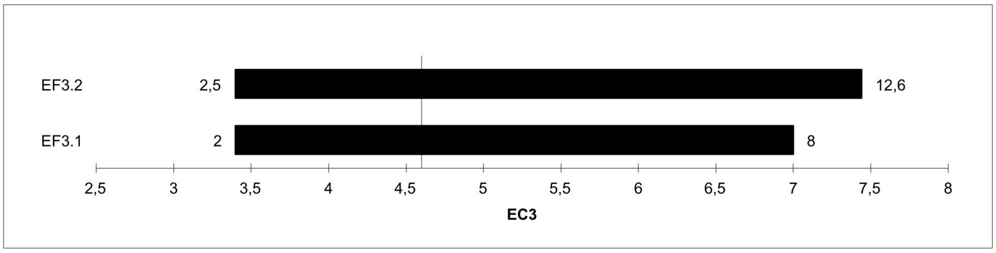


Figure B.17: Sensitivity analysis of EC3 with respect to OB3: tornado diagram.

	Corresponding Input Value			Input Value as % of Base			EC3 Output Value			
Input Variable	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	Swing
EF3.2	2,5	5,5	12,6	45,5%	100,0%	229,1%	3,4	4,6	7,44	4,04
EF3.1	2	4	8	50,0%	100,0%	200,0%	3,4	4,6	7	3,6

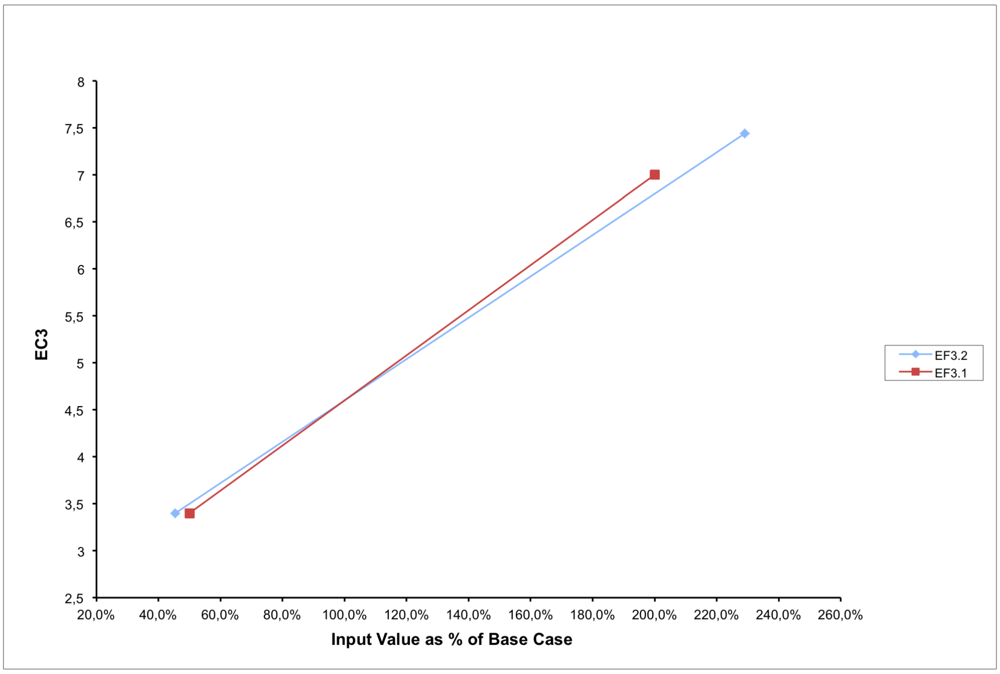


Figure B.18: Sensitivity analysis of EC3 with respect to OB3: spider chart.

B.1.2 Internal Analysis

B.1.2.1 IC1 vs OB1

Figures B.19, B.20 and B.21 show sensitivity analysis of IC1 with respect to OB1.

	Corresponding Input Value			IC1 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
IF12	1	5,3	13,5	4,3	5,5	7,8	3,5	39,3%
IF14	2,2	5,6	13,5	4,5	5,5	7,9	3,4	36,8%
IF11	2	5,8	10,5	4,6	5,5	6,7	2,0	13,3%
IF13	1,9	5,5	12	4,9	5,5	6,7	1,8	10,6%

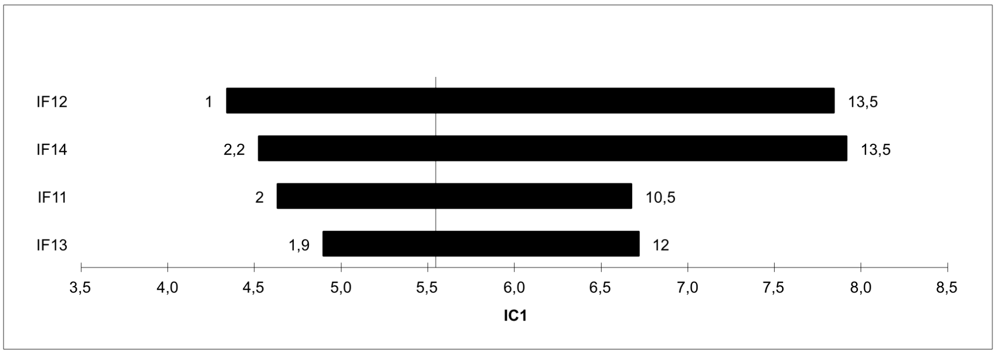


Figure B.19: Sensitivity analysis of IC1 with respect to OB1: tornado diagram.

	Corresponding Input Values			IC1 Output Value			
Input Variables	Low Output	Base Case	High Output	Low	Base	High	Swing
IF12 & IF14	1 & 2,2	5,3 & 5,6	13,5 & 13,5	3,3	5,5	10,2	6,9
IF11 & IF12	2 & 1	5,8 & 5,3	10,5 & 13,5	3,4	5,5	9,0	5,5
IF11 & IF14	2 & 2,2	5,8 & 5,6	10,5 & 13,5	3,6	5,5	9,0	5,4
IF12 & IF13	1 & 1,9	5,3 & 5,5	13,5 & 12	3,7	5,5	9,0	5,3
IF13 & IF14	1,9 & 2,2	5,5 & 5,6	12 & 13,5	3,9	5,5	9,1	5,2
IF11 & IF13	2 & 1,9	5,8 & 5,5	10,5 & 12	4,0	5,5	7,8	3,9

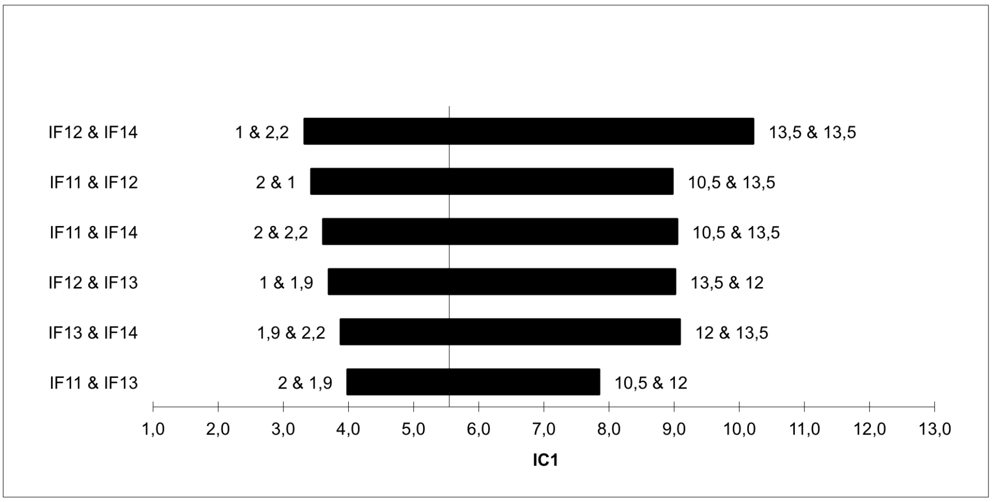


Figure B.20: Sensitivity analysis of IC1 with respect to OB1: two factors tornado diagram.

Input Variable	Corresponding Input Value Low Output	Base Case	High Output	Input Value as % of Base Low %	Base %	High %	IC1 Output Value Low	Base	High	Swing
IF12	1	5,3	13,5	18,9%	100,0%	254,7%	4,3	5,5	7,8	3,5
IF14	2,2	5,6	13,5	39,3%	100,0%	241,1%	4,5	5,5	7,9	3,4
IF11	2	5,8	10,5	34,5%	100,0%	181,0%	4,6	5,5	6,7	2,0
IF13	1,9	5,5	12	34,5%	100,0%	218,2%	4,9	5,5	6,7	1,8

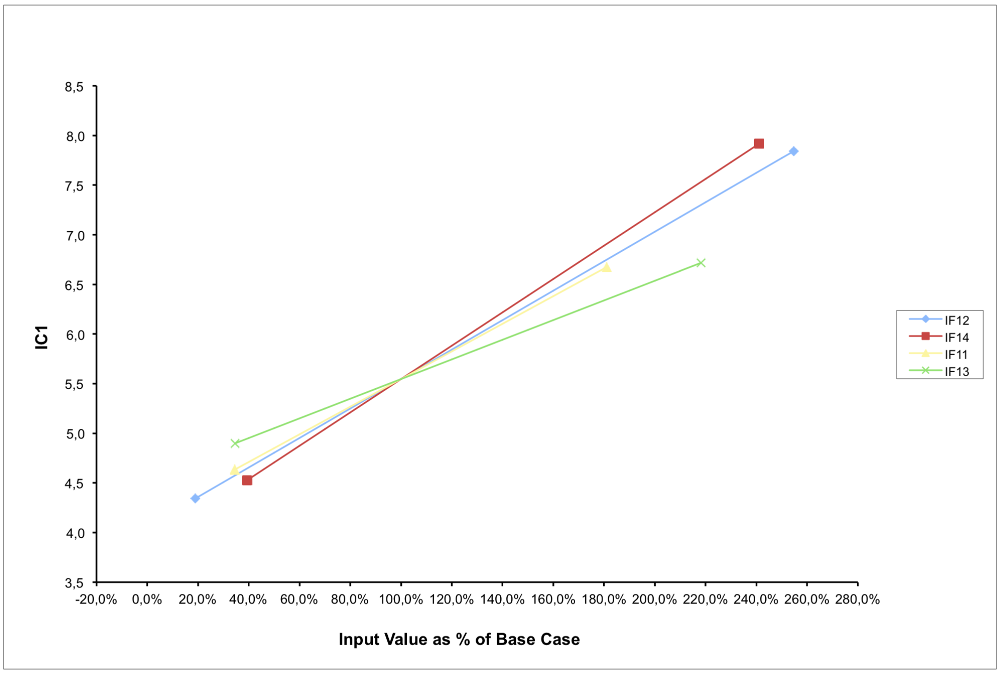


Figure B.21: Sensitivity analysis of IC1 with respect to OB1: spider chart.

B.1.2.2 IC1 vs OB2

Figures B.22, B.23 and B.24 show sensitivity analysis of IC1 with respect to OB2.

Input Variable	Corresponding Input Value Low Output	Base Case	High Output	IC1 Output Value Low	Base	High	Swing	Percent Swing^2
IF12	1	5,3	13,5	4,5	5,6	7,6	3,1	34,1%
IF14	2,2	5,6	13,5	4,7	5,6	7,5	2,8	27,9%
IF13	1,9	5,5	12	4,7	5,6	7,2	2,5	22,3%
IF11	2	5,8	10,5	4,6	5,6	6,7	2,1	15,8%

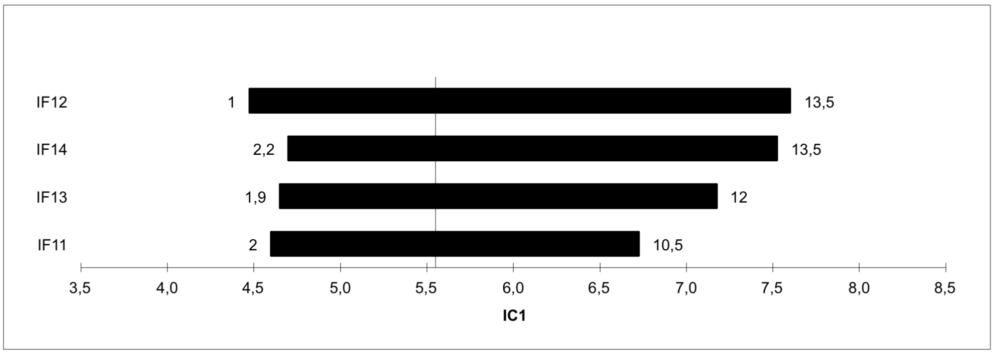


Figure B.22: Sensitivity analysis of IC1 with respect to OB2: tornado diagram.

Input Variables	Corresponding Input Values Low Output	Base Case	High Output	IC1 Output Value Low	Base	High	Swing
IF12 & IF14	1 & 2,2	5,3 & 5,6	13,5 & 13,5	3,6	5,6	9,6	6,0
IF12 & IF13	1 & 1,9	5,3 & 5,5	13,5 & 12	3,6	5,6	9,2	5,7
IF13 & IF14	1,9 & 2,2	5,5 & 5,6	12 & 13,5	3,8	5,6	9,2	5,4
IF11 & IF12	2 & 1	5,8 & 5,3	10,5 & 13,5	3,5	5,6	8,8	5,3
IF11 & IF14	2 & 2,2	5,8 & 5,6	10,5 & 13,5	3,8	5,6	8,7	5,0
IF11 & IF13	2 & 1,9	5,8 & 5,5	10,5 & 12	3,7	5,6	8,4	4,7

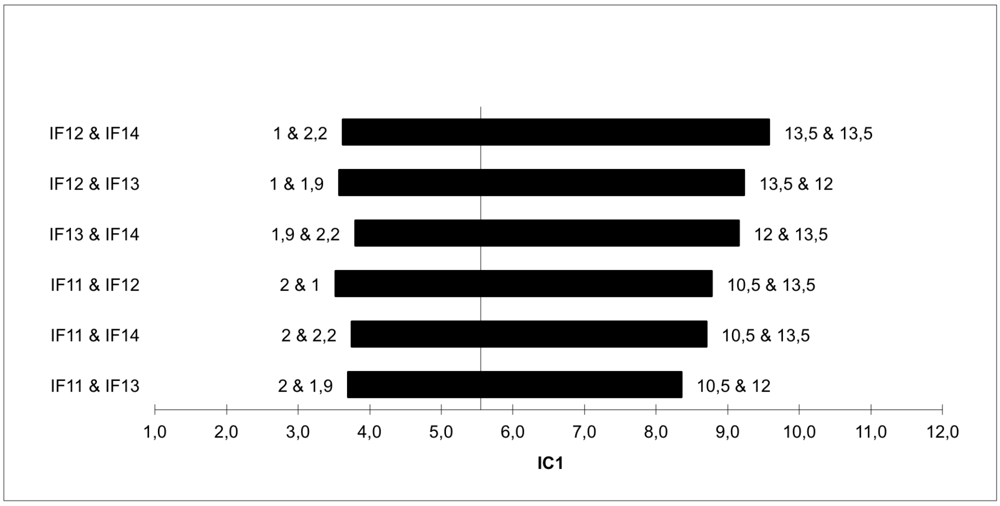


Figure B.23: Sensitivity analysis of IC1 with respect to OB2: two factors tornado diagram.

Input Variable	Corresponding Input Value Low Output	Base Case	High Output	Input Value as % of Base Low %	Base %	High %	IC1 Output Value Low	Base	High	Swing
IF12	1	5,3	13,5	18,9%	100,0%	254,7%	4,5	5,6	7,6	3,1
IF14	2,2	5,6	13,5	39,3%	100,0%	241,1%	4,7	5,6	7,5	2,8
IF13	1,9	5,5	12	34,5%	100,0%	218,2%	4,7	5,6	7,2	2,5
IF11	2	5,8	10,5	34,5%	100,0%	181,0%	4,6	5,6	6,7	2,1

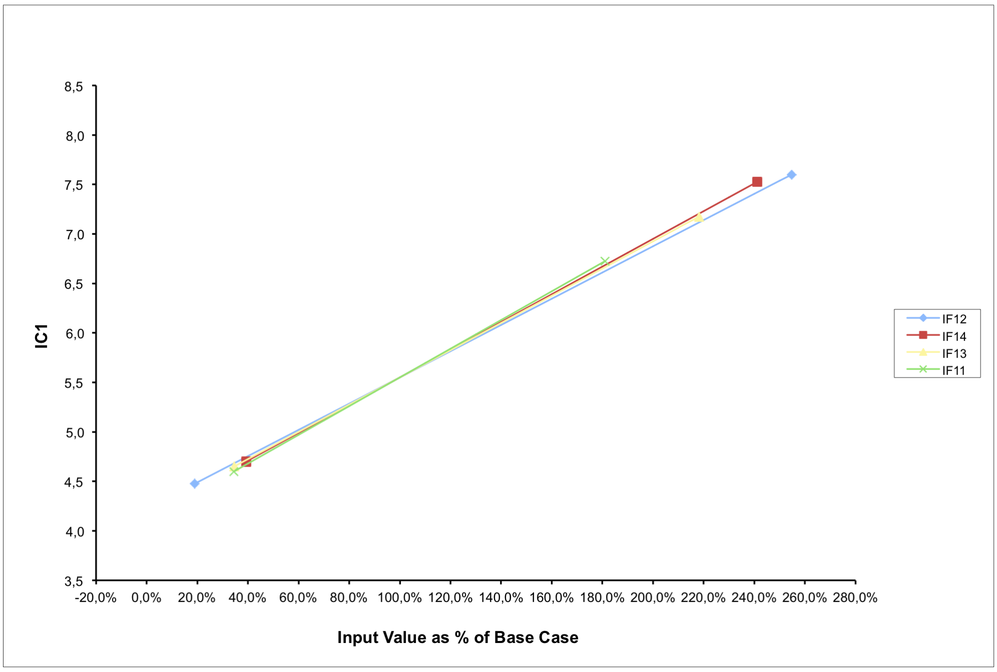


Figure B.24: Sensitivity analysis of IC1 with respect to OB2: spider chart.

B.1.2.3 IC1 vs OB3

Figures B.25, B.26 and B.27 show sensitivity analysis of IC1 with respect to OB3.

	Corresponding Input Value			IC1 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
IF13	1,9	5,5	12	4,3	5,6	7,9	3,5	44,2%
IF11	2	5,8	10,5	4,3	5,6	7,2	3,0	31,3%
IF12	1	5,3	13,5	4,8	5,6	7,1	2,3	17,9%
IF14	2,2	5,6	13,5	5,2	5,6	6,5	1,4	6,5%

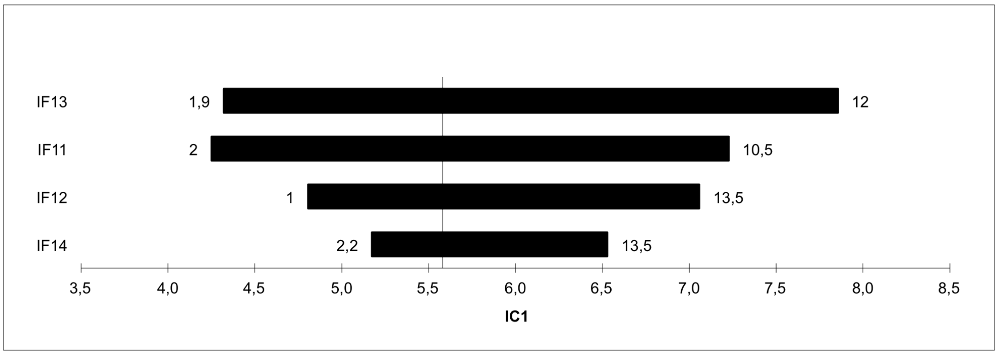


Figure B.25: Sensitivity analysis of IC1 with respect to OB3: tornado diagram.

	Corresponding Input Values			IC1 Output Value			
Input Variables	Low Output	Base Case	High Output	Low	Base	High	Swing
IF11 & IF13	2 & 1,9	5,8 & 5,5	10,5 & 12	3,0	5,6	9,5	6,5
IF12 & IF13	1 & 1,9	5,3 & 5,5	13,5 & 12	3,5	5,6	9,3	5,8
IF11 & IF12	2 & 1	5,8 & 5,3	10,5 & 13,5	3,5	5,6	8,7	5,2
IF13 & IF14	1,9 & 2,2	5,5 & 5,6	12 & 13,5	3,9	5,6	8,8	4,9
IF11 & IF14	2 & 2,2	5,8 & 5,6	10,5 & 13,5	3,8	5,6	8,2	4,3
IF12 & IF14	1 & 2,2	5,3 & 5,6	13,5 & 13,5	4,4	5,6	8,0	3,6

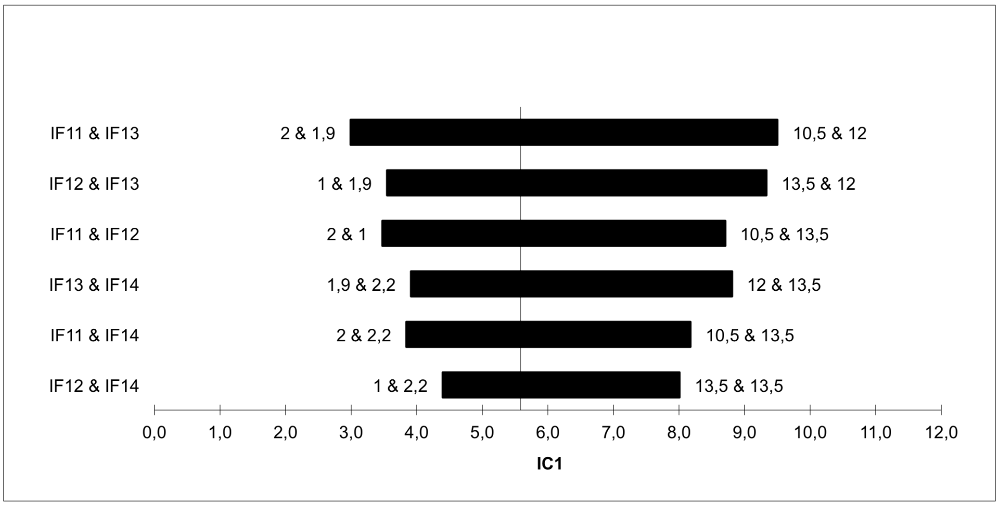


Figure B.26: Sensitivity analysis of IC1 with respect to OB3: two factors tornado diagram.

Input Variable	Corresponding Input Value: Low Output	Base Case	High Output	Input Value as % of Base: Low %	Base %	High %	IC1 Output Value: Low	Base	High	Swing
IF13	1,9	5,5	12	34,5%	100,0%	218,2%	4,3	5,6	7,9	3,5
IF11	2	5,8	10,5	34,5%	100,0%	181,0%	4,3	5,6	7,2	3,0
IF12	1	5,3	13,5	18,9%	100,0%	254,7%	4,8	5,6	7,1	2,3
IF14	2,2	5,6	13,5	39,3%	100,0%	241,1%	5,2	5,6	6,5	1,4

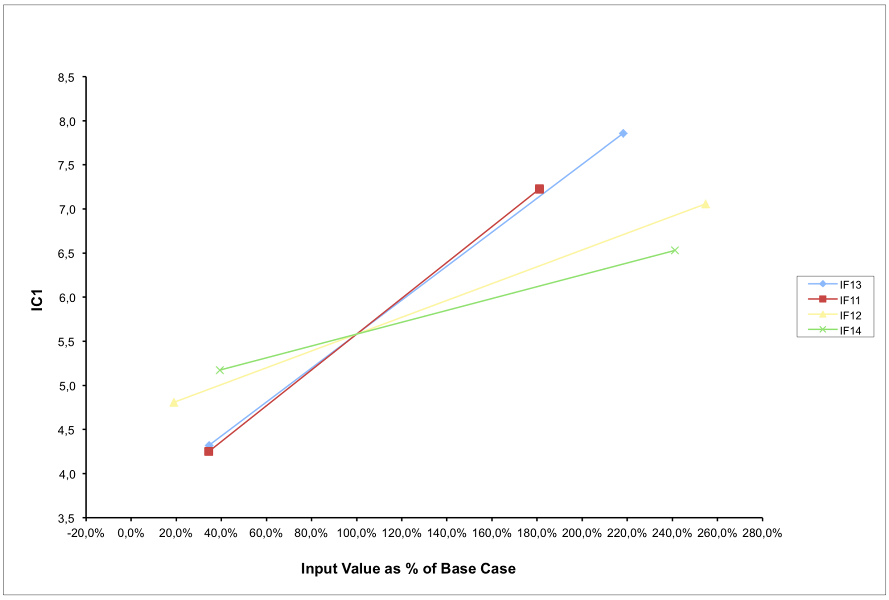


Figure B.27: Sensitivity analysis of IC1 with respect to OB3: spider chart.

B.1.2.4 IC2 vs OB1

Figures B.28, B.29 and B.30 show sensitivity analysis of IC2 with respect to OB1.

Input Variable	Corresponding Input Value: Low Output	Base Case	High Output	IC2 Output Value: Low	Base	High	Swing	Percent Swing^2
IF21	2,7	5,8	11,4	3,2	4,9	7,9	4,7	75,9%
IF22	1	3	9	4,3	4,9	6,7	2,4	19,8%
IF23	2	5,5	9	4,4	4,9	5,5	1,1	4,3%

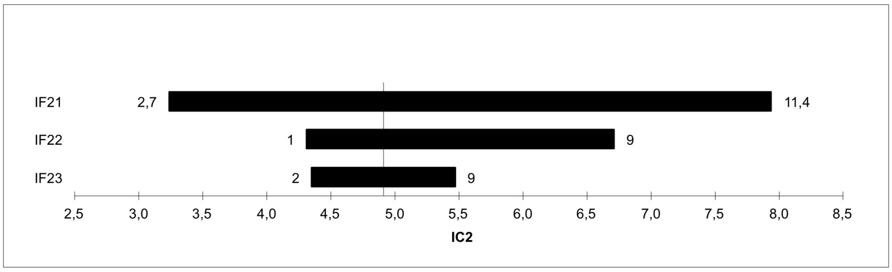


Figure B.28: Sensitivity analysis of IC1 with respect to OB1: tornado diagram.

	Corresponding Input Values			IC2 Output Value			
Input Variables	Low Output	Base Case	High Output	Low	Base	High	Swing
IF21 & IF22	2,7 & 1	5,8 & 3	11,4 & 9	2,6	4,9	9,7	7,1
IF21 & IF23	2,7 & 2	5,8 & 5,5	11,4 & 9	2,7	4,9	8,5	5,8
IF22 & IF23	1 & 2	3 & 5,5	9 & 9	3,8	4,9	7,3	3,5

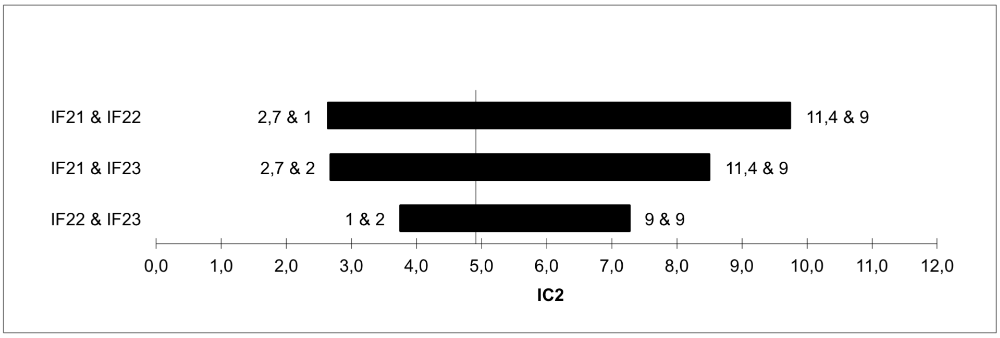


Figure B.29: Sensitivity analysis of IC1 with respect to OB1: two factors tornado diagram.

	Corresponding Input Value			Input Value as % of Base			IC2 Output Value			
Input Variable	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	Swing
IF21	2,7	5,8	11,4	46,6%	100,0%	196,6%	3,2	4,9	7,9	4,7
IF22	1	3	9	33,3%	100,0%	300,0%	4,3	4,9	6,7	2,4
IF23	2	5,5	9	36,4%	100,0%	163,6%	4,4	4,9	5,5	1,1

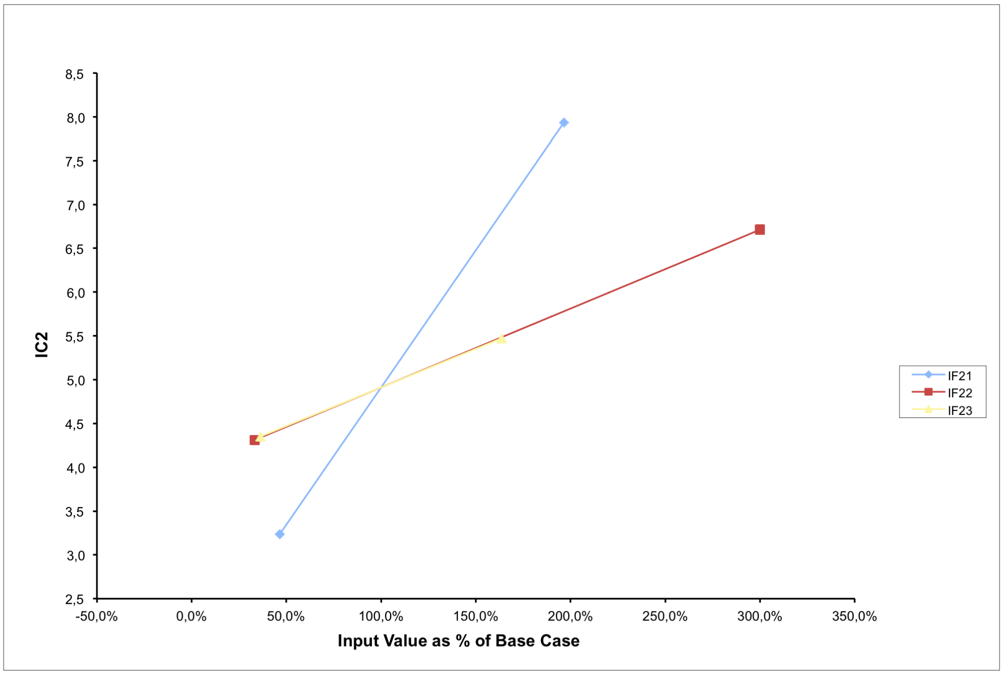


Figure B.30: Sensitivity analysis of IC2 with respect to OB1: spider chart.

B.1.2.5 IC2 vs OB2

Figures B.31, B.32 and B.33 show sensitivity analysis of IC2 with respect to OB2.

Input Variable	Corresponding Input Value			IC2 Output Value			Swing	Percent Swing^2
	Low Output	Base Case	High Output	Low	Base	High		
IF21	2,7	5,8	11,4	3,4	4,9	7,7	4,4	71,5%
IF22	1	3	9	4,3	4,9	6,7	2,3	20,3%
IF23	2	5,5	9	4,2	4,9	5,7	1,5	8,2%

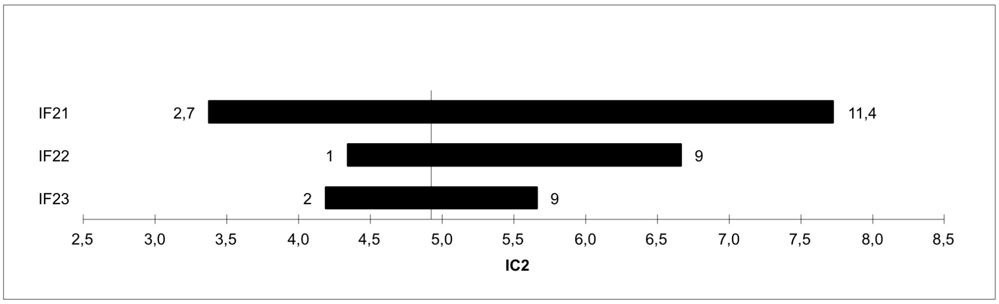


Figure B.31: Sensitivity analysis of IC2 with respect to OB2: tornado diagram.

Input Variables	Corresponding Input Values			IC2 Output Value			Swing
	Low Output	Base Case	High Output	Low	Base	High	
IF21 & IF22	2,7 & 1	5,8 & 3	11,4 & 9	2,8	4,9	9,5	6,7
IF21 & IF23	2,7 & 2	5,8 & 5,5	11,4 & 9	2,6	4,9	8,5	5,8
IF22 & IF23	1 & 2	3 & 5,5	9 & 9	3,6	4,9	7,4	3,8

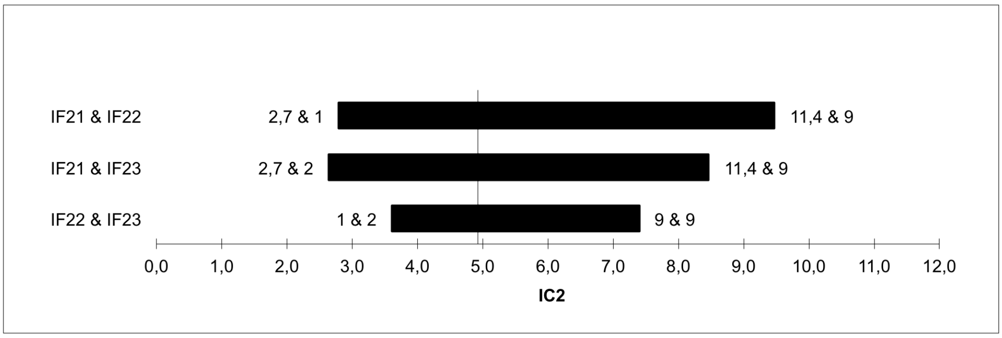


Figure B.32: Sensitivity analysis of IC2 with respect to OB2: two factors tornado diagram.

Input Variable	Corresponding Input Value: Low Output	Base Case	High Output	Input Value as % of Base: Low %	Base %	High %	IC2 Output Value: Low	Base	High	Swing
IF21	2,7	5,8	11,4	46,6%	100,0%	196,6%	3,4	4,9	7,7	4,4
IF22	1	3	9	33,3%	100,0%	300,0%	4,3	4,9	6,7	2,3
IF23	2	5,5	9	36,4%	100,0%	163,6%	4,2	4,9	5,7	1,5

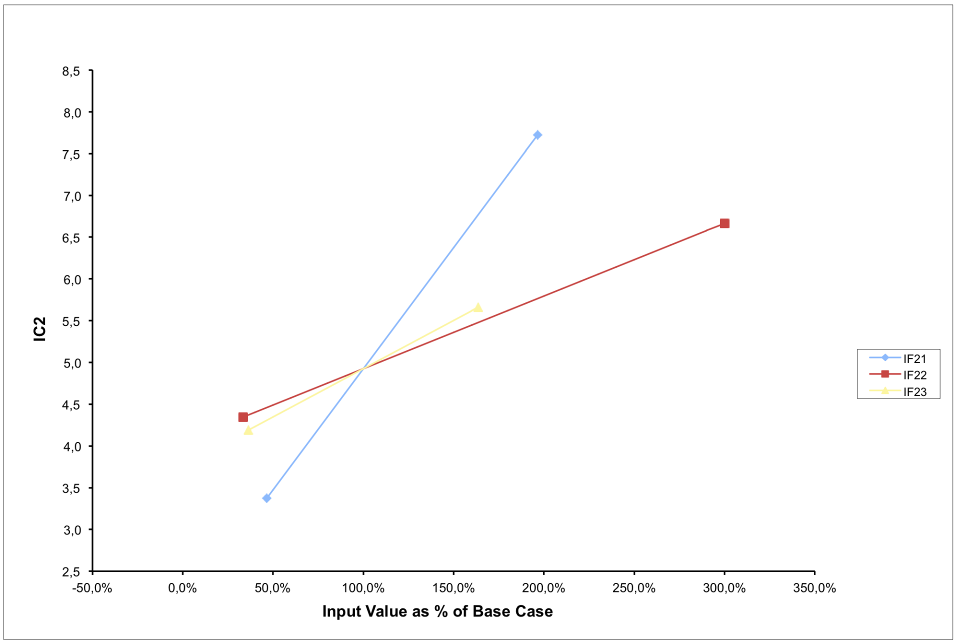


Figure B.33: Sensitivity analysis of IC2 with respect to OB2: spider chart.

B.1.2.6 IC2 vs OB3

Figures B.34, B.35 and B.36 show sensitivity analysis of IC2 with respect to OB3.

Input Variable	Corresponding Input Value: Low Output	Base Case	High Output	IC2 Output Value: Low	Base	High	Swing	Percent Swing^2
IF22	1	3	9	3,8	4,6	7,0	3,2	48,5%
IF23	2	5,5	9	3,2	4,6	6,0	2,8	37,1%
IF21	2,7	5,8	11,4	3,9	4,6	5,7	1,7	14,3%

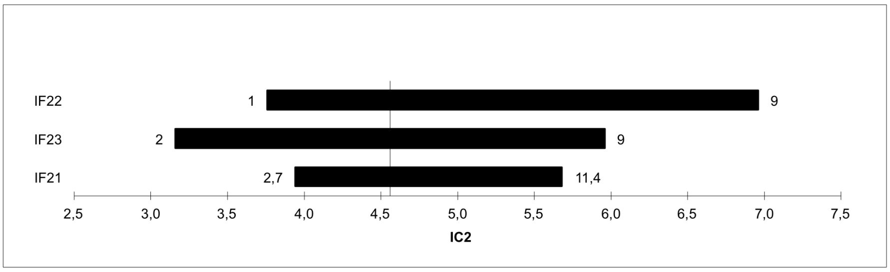


Figure B.34: Sensitivity analysis of IC2 with respect to OB3: tornado diagram.

Input Variables	Low Output	Base Case	High Output	Low	Base	High	Swing
	Corresponding Input Values			IC2 Output Value			
IF22 & IF23	1 & 2	3 & 5,5	9 & 9	2,4	4,6	8,4	6,0
IF21 & IF22	2,7 & 1	5,8 & 3	11,4 & 9	3,1	4,6	8,1	4,9
IF21 & IF23	2,7 & 2	5,8 & 5,5	11,4 & 9	2,5	4,6	7,1	4,5

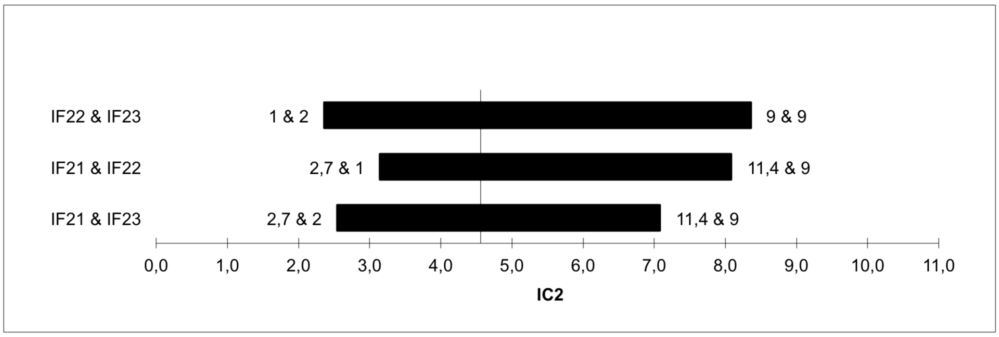


Figure B.35: Sensitivity analysis of IC2 with respect to OB3: two factors tornado diagram.

Input Variable	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	Swing
	Corresponding Input Value			Input Value as % of Base			IC2 Output Value			
IF22	1	3	9	33,3%	100,0%	300,0%	3,8	4,6	7,0	3,2
IF23	2	5,5	9	36,4%	100,0%	163,6%	3,2	4,6	6,0	2,8
IF21	2,7	5,8	11,4	46,6%	100,0%	196,6%	3,9	4,6	5,7	1,7

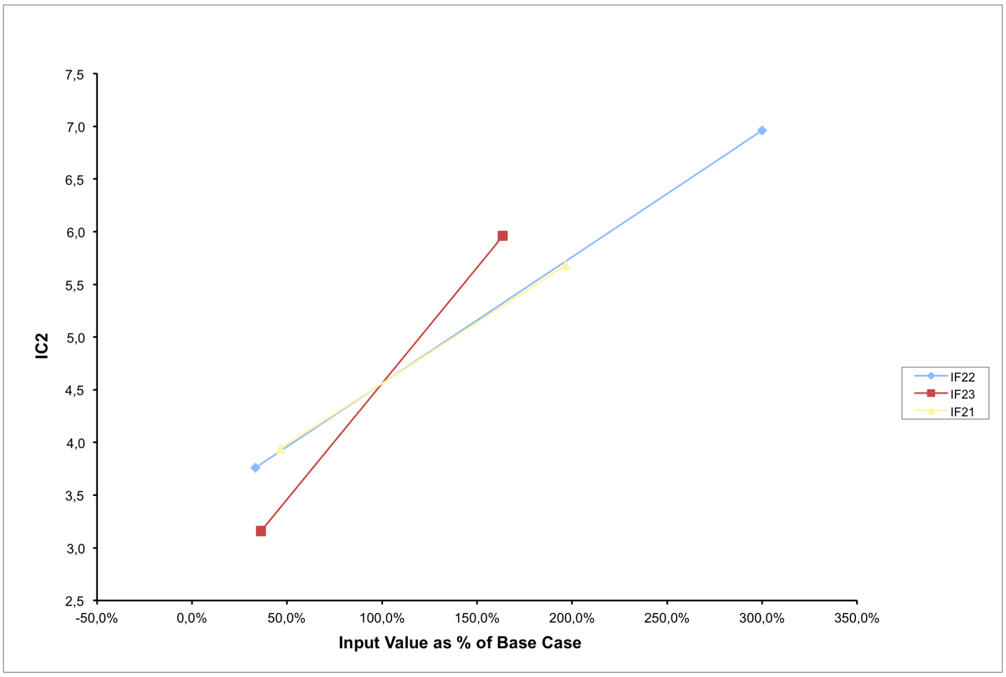


Figure B.36: Sensitivity analysis of IC2 with respect to OB3: spider chart.

B.1.2.7 IC3 vs OB1

Figures B.37 and B.38 show sensitivity analysis of IC3 with respect to OB1.

	Corresponding Input Value			IC3 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
IF32	3	7	7	3,0	5,4	5,4	2,4	59,0%
IF31	3	3	8	5,4	5,4	7,4	2,0	41,0%

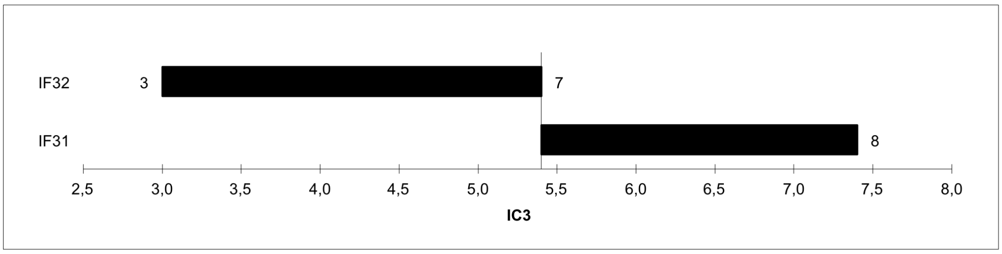


Figure B.37: Sensitivity analysis of IC3 with respect to OB1: tornado diagram.

	Corresponding Input Value			Input Value as % of Base			IC3 Output Value			
Input Variable	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	Swing
IF32	3	7	7	42,9%	100,0%	100,0%	3,0	5,4	5,4	2,4
IF31	3	3	8	100,0%	100,0%	266,7%	5,4	5,4	7,4	2,0

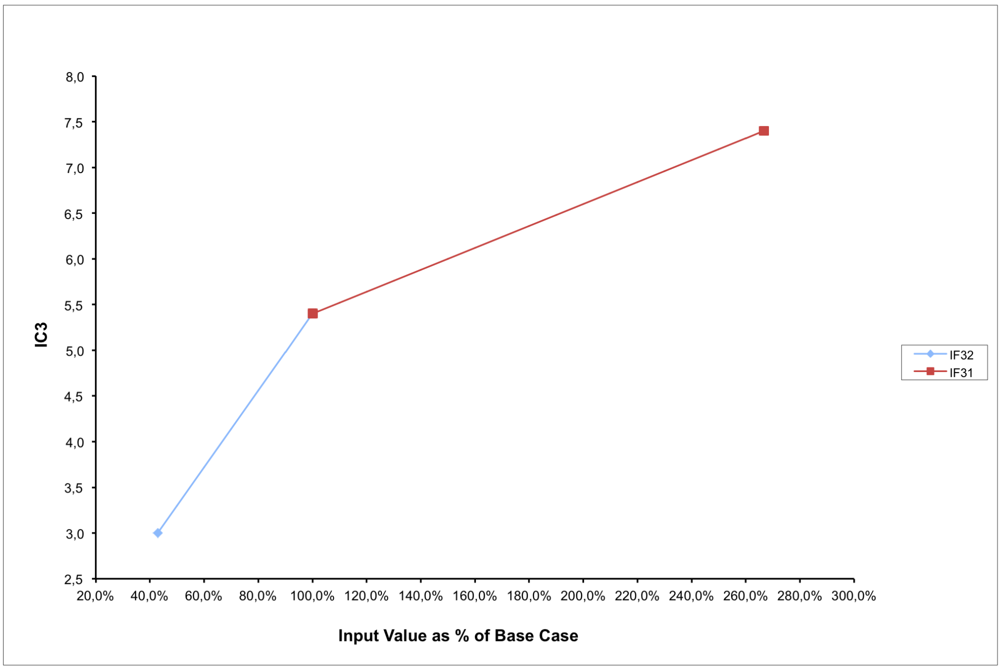


Figure B.38: Sensitivity analysis of IC3 with respect to OB1: spider chart.

B.1.2.8 IC3 vs OB2

Figures B.39 and B.40 show sensitivity analysis of IC3 with respect to OB2.

	Corresponding Input Value			IC3 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
IF32	3	7	7	3,0	5,8	5,8	2,8	77,7%
IF31	3	3	8	5,8	5,8	7,3	1,5	22,3%

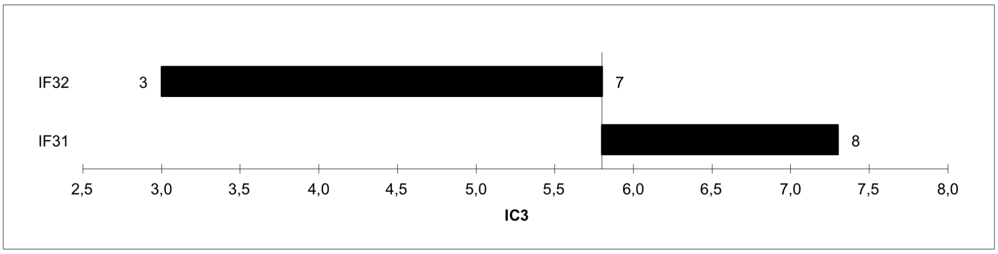


Figure B.39: Sensitivity analysis of IC3 with respect to OB2: tornado diagram.

	Corresponding Input Value			Input Value as % of Base			IC3 Output Value			
Input Variable	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	Swing
IF32	3	7	7	42,9%	100,0%	100,0%	3,0	5,8	5,8	2,8
IF31	3	3	8	100,0%	100,0%	266,7%	5,8	5,8	7,3	1,5

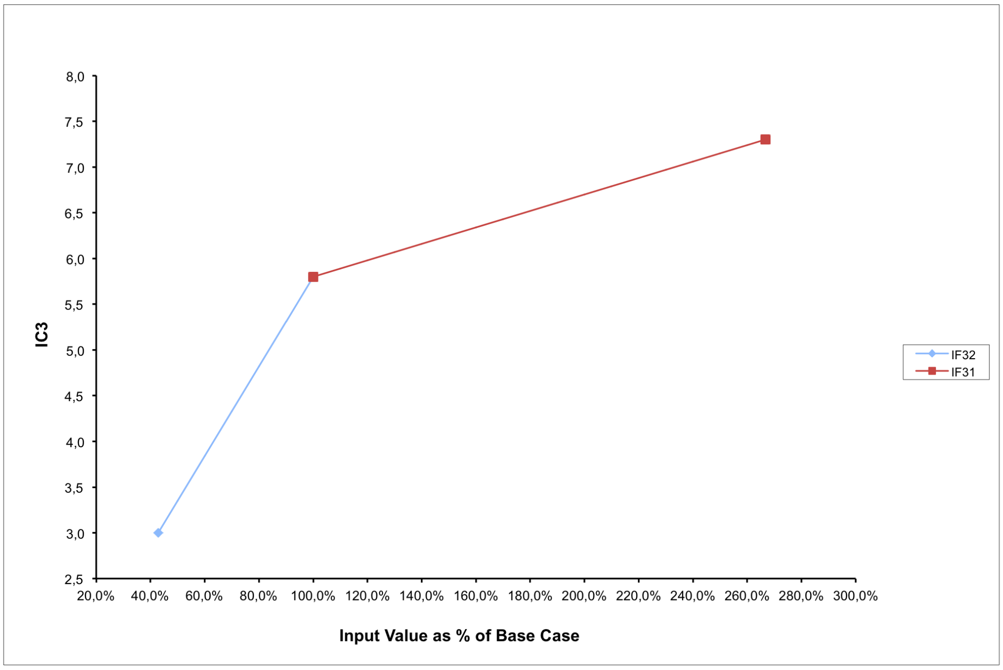


Figure B.40: Sensitivity analysis of IC2 with respect to OB2: spider chart.

B.1.2.9 IC3 vs OB3

Figures B.41 and B.42 show sensitivity analysis of IC3 with respect to OB3.

	Corresponding Input Value			IC3 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
IF32	3	7	7	3,0	6,2	6,2	3,2	91,1%
IF31	3	3	8	6,2	6,2	7,2	1,0	8,9%

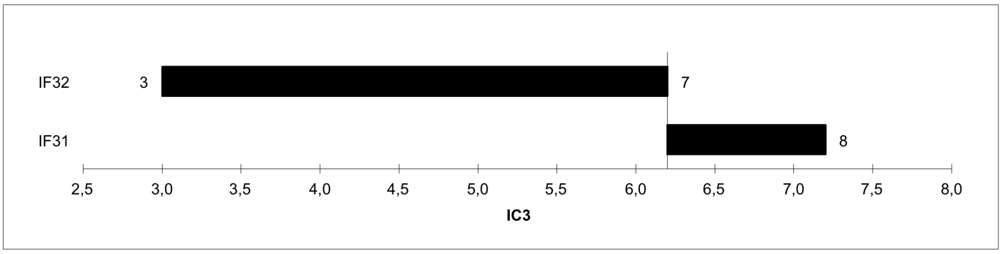


Figure B.41: Sensitivity analysis of IC3 with respect to OB3: tornado diagram.

	Corresponding Input Value			Input Value as % of Base			IC3 Output Value			
Input Variable	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	Swing
IF32	3	7	7	42,9%	100,0%	100,0%	3,0	6,2	6,2	3,2
IF31	3	3	8	100,0%	100,0%	266,7%	6,2	6,2	7,2	1,0

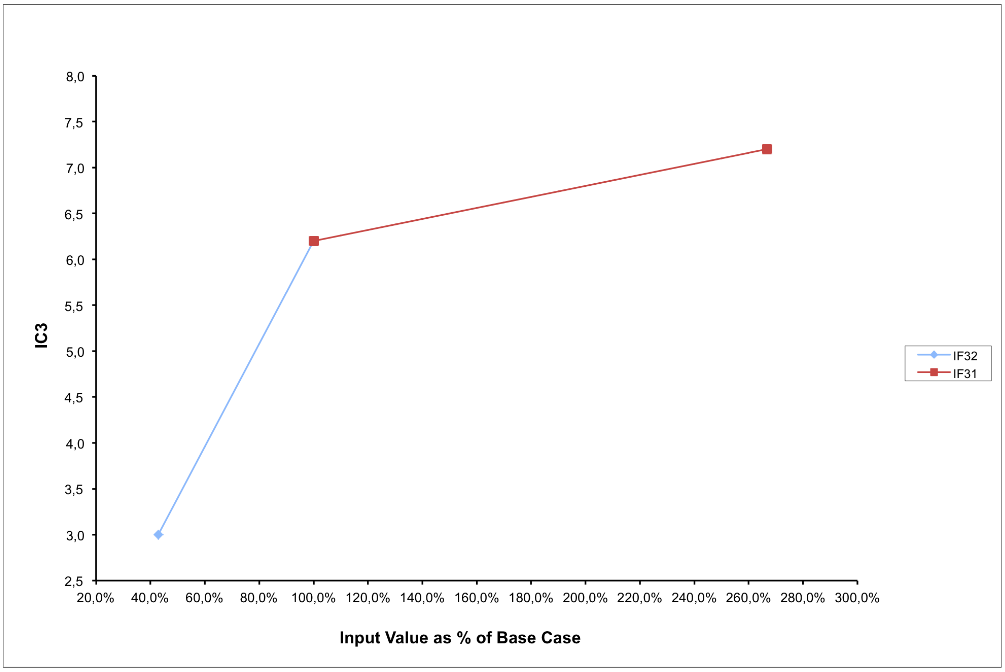


Figure B.42: Sensitivity analysis of IC3 with respect to OB3: spider chart.

B.2 Sensitivity analysis of level 3 with respect to level 2 - Characteristics vs Objectives

B.2.1 External Analysis

B.2.1.1 EC vs OB1

Figures B.43, B.44 and B.45 show sensitivity analysis of External Characteristics with respect to OB1.

	Corresponding Input Value			OB1 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
EC2	1,54	4,00	8,10	3,10	4,51	6,84	3,74	81,4%
EC1	2,80	5,50	9,70	3,86	4,51	5,51	1,66	16,0%
EC3	3,29	4,77	6,83	4,23	4,51	4,90	0,67	2,6%

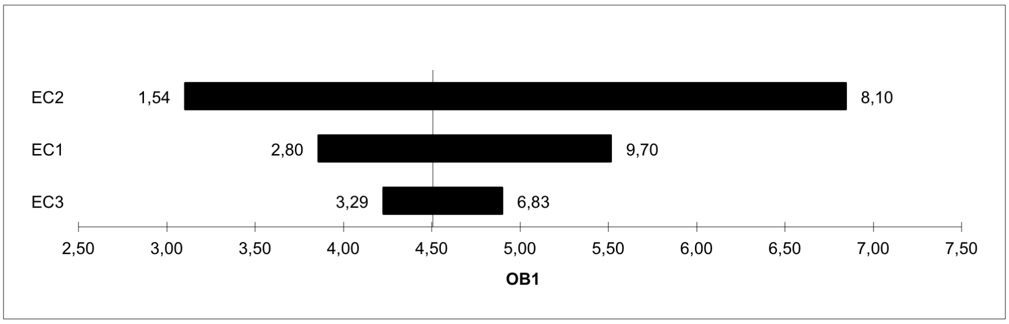


Figure B.43: Sensitivity analysis of External Characteristics with respect to OB1: tornado diagram.

	Corresponding Input Values			OB1 Output Value			
Input Variables	Low Output	Base Case	High Output	Low	Base	High	Swing
EC1 & EC2	2,80 & 1,54	5,50 & 4,00	9,70 & 8,10	2,46	4,51	7,85	5,40
EC2 & EC3	1,54 & 3,29	4,00 & 4,77	8,10 & 6,83	2,82	4,51	7,23	4,41
EC1 & EC3	2,80 & 3,29	5,50 & 4,77	9,70 & 6,83	3,58	4,51	5,91	2,33

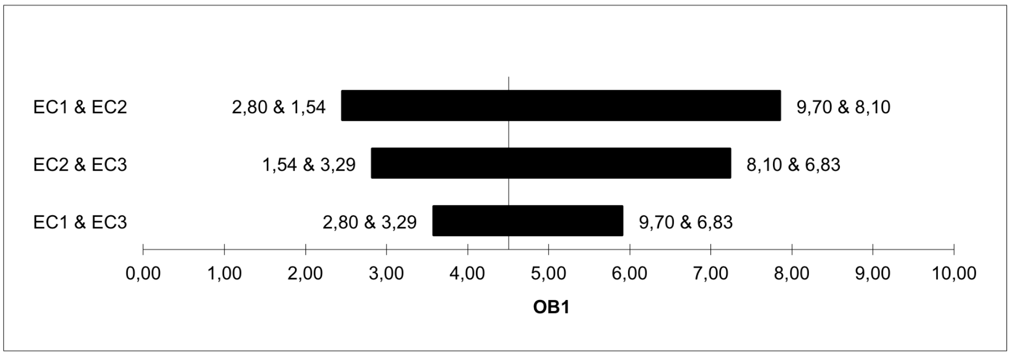


Figure B.44: Sensitivity analysis of External Characteristics with respect to OB1: two factors tornado diagram.

Input Variable	Corresponding Input Value			Input Value as % of Base			OB1 Output Value			Swing
	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	
EC2	1,54	4,00	8,10	38,5%	100,0%	202,5%	3,10	4,51	6,84	3,74
EC1	2,80	5,50	9,70	50,9%	100,0%	176,4%	3,86	4,51	5,51	1,66
EC3	3,29	4,77	6,83	69,0%	100,0%	143,2%	4,23	4,51	4,90	0,67

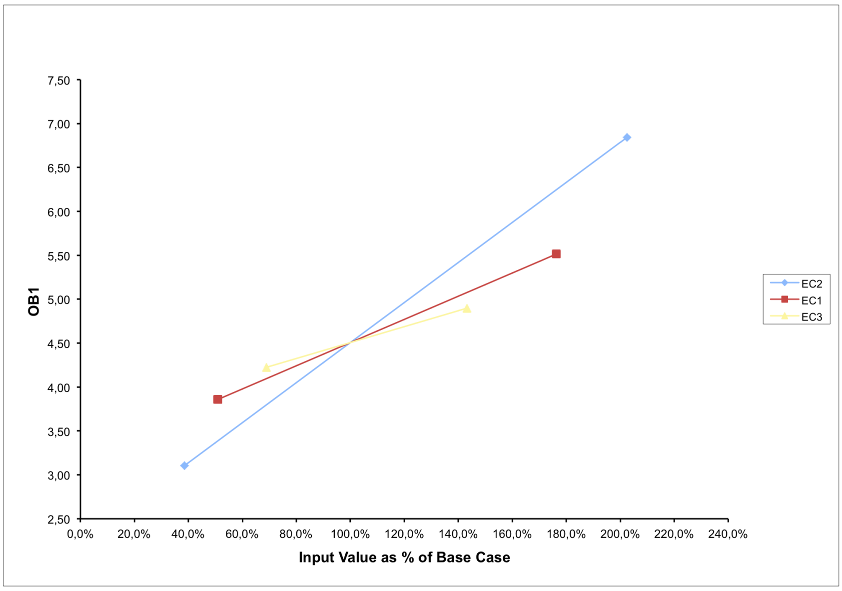


Figure B.45: Sensitivity analysis of External Characteristics with respect to OB1: spider chart.

B.2.1.2 EC vs OB2

Figures B.46, B.47 and B.48 show sensitivity analysis of External Characteristics with respect to OB2.

Input Variable	Corresponding Input Value			OB2 Output Value			Swing	Percent Swing^2
	Low Output	Base Case	High Output	Low	Base	High		
EC1	2,35	5,50	10,38	4,05	4,78	5,90	1,85	40,5%
EC3	3,28	4,76	6,82	4,09	4,78	5,72	1,63	31,5%
EC2	2,40	4,26	7,36	4,20	4,78	5,74	1,54	28,1%

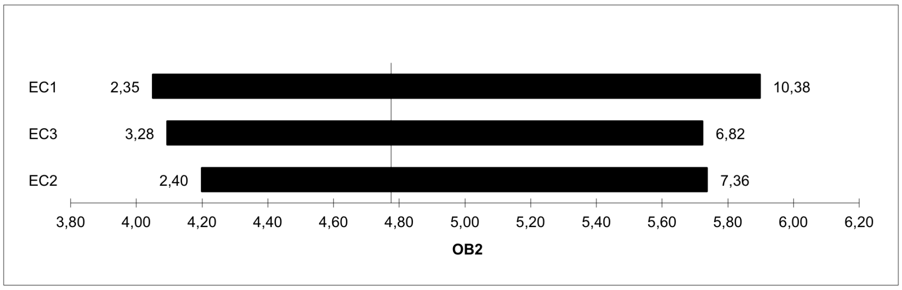


Figure B.46: Sensitivity analysis of External Characteristics with respect to OB2: tornado diagram.

Input Variables	Corresponding Input Values: Low Output	Base Case	High Output	OB2 Output Value: Low	Base	High	Swing
EC1 & EC3	2,35 & 3,28	5,50 & 4,76	10,38 & 6,82	3,37	4,78	6,85	3,48
EC1 & EC2	2,35 & 2,40	5,50 & 4,26	10,38 & 7,36	3,47	4,78	6,86	3,38
EC2 & EC3	2,40 & 3,28	4,26 & 4,76	7,36 & 6,82	3,52	4,78	6,68	3,17

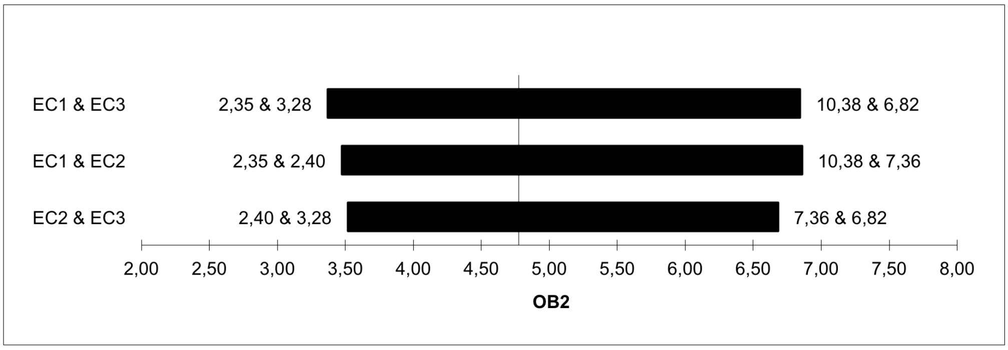


Figure B.47: Sensitivity analysis of External Characteristics with respect to OB2: two factors tornado diagram.

Input Variable	Corresponding Input Value: Low Output	Base Case	High Output	Input Value as % of Base: Low %	Base %	High %	Output Value: Low	Base	High	Swing
EC1	2,35	5,50	10,38	42,7%	100,0%	188,7%	4,05	4,78	5,90	1,85
EC3	3,28	4,76	6,82	68,9%	100,0%	143,3%	4,09	4,78	5,72	1,63
EC2	2,40	4,26	7,36	56,3%	100,0%	172,8%	4,20	4,78	5,74	1,54

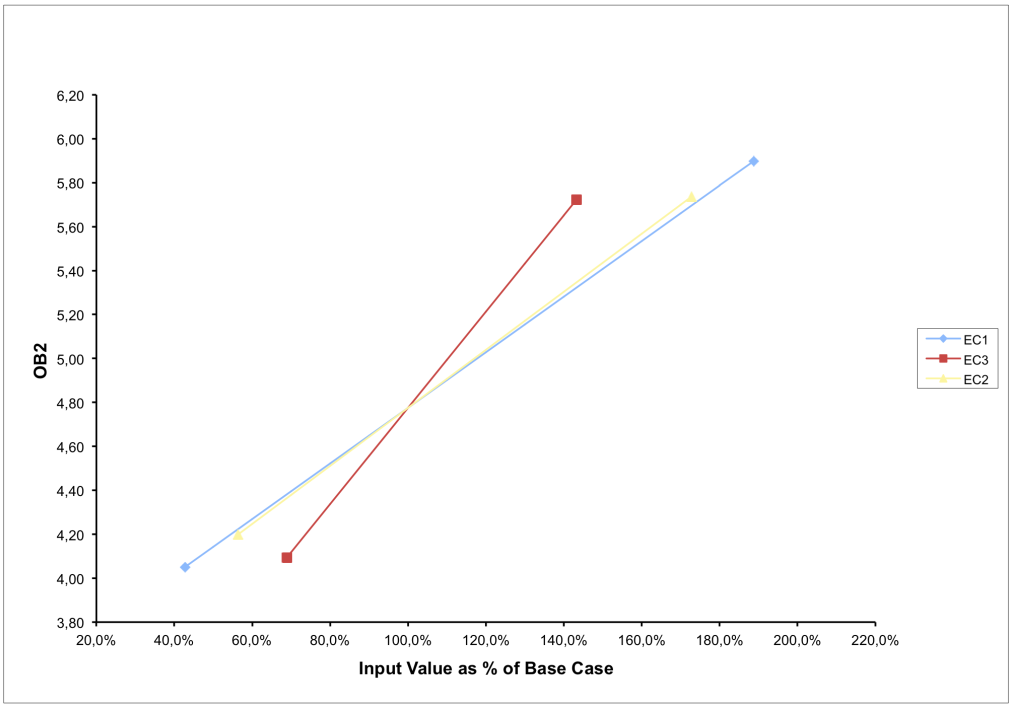


Figure B.48: Sensitivity analysis of External Characteristics with respect to OB2: spider chart.

B.2.1.3 EC vs OB3

Figures B.49, B.50 and B.51 show sensitivity analysis of External Characteristics with respect to OB3.

	Corresponding Input Value			OB3 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
EC2	0,98	4,53	7,37	2,83	4,82	6,41	3,58	76,0%
EC1	1,10	5,50	8,30	3,63	4,82	5,57	1,94	22,4%
EC3	3,44	4,69	6,44	4,61	4,82	5,12	0,51	1,5%

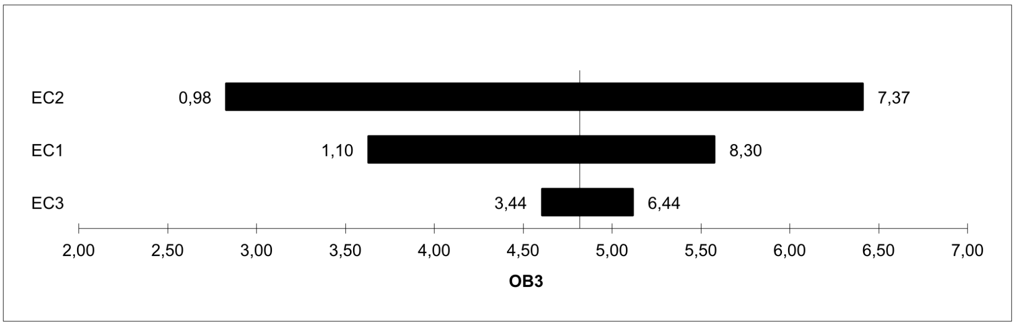


Figure B.49: Sensitivity analysis of External Characteristics with respect to OB3: tornado diagram.

	Corresponding Input Values			OB3 Output Value			
Input Variables	Low Output	Base Case	High Output	Low	Base	High	Swing
EC1 & EC2	1,10 & 0,98	5,50 & 4,53	8,30 & 7,37	1,64	4,82	7,16	5,52
EC2 & EC3	0,98 & 3,44	4,53 & 4,69	7,37 & 6,44	2,62	4,82	6,71	4,09
EC1 & EC3	1,10 & 3,44	5,50 & 4,69	8,30 & 6,44	3,42	4,82	5,87	2,45

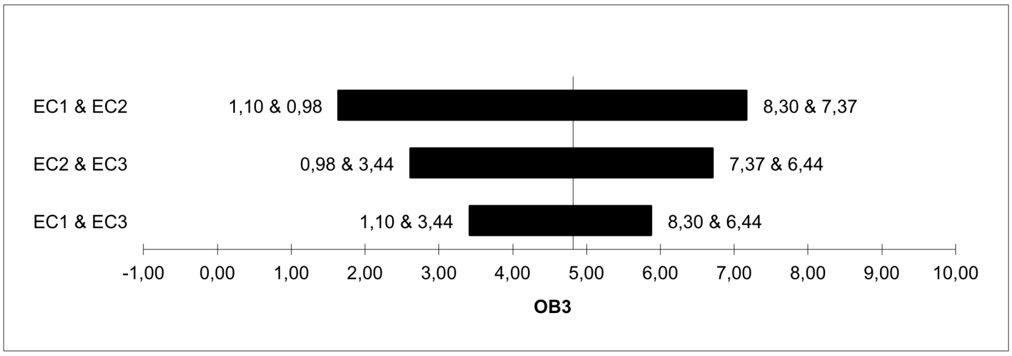


Figure B.50: Sensitivity analysis of External Characteristics with respect to OB3: two factors tornado diagram.

Input Variable	Corresponding Input Value			Input Value as % of Base			OB3 Output Value			
	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	Swing
EC2	0,98	4,53	7,37	21,6%	100,0%	162,7%	2,83	4,82	6,41	3,58
EC1	1,10	5,50	8,30	20,0%	100,0%	150,9%	3,63	4,82	5,57	1,94
EC3	3,44	4,69	6,44	73,3%	100,0%	137,4%	4,61	4,82	5,12	0,51

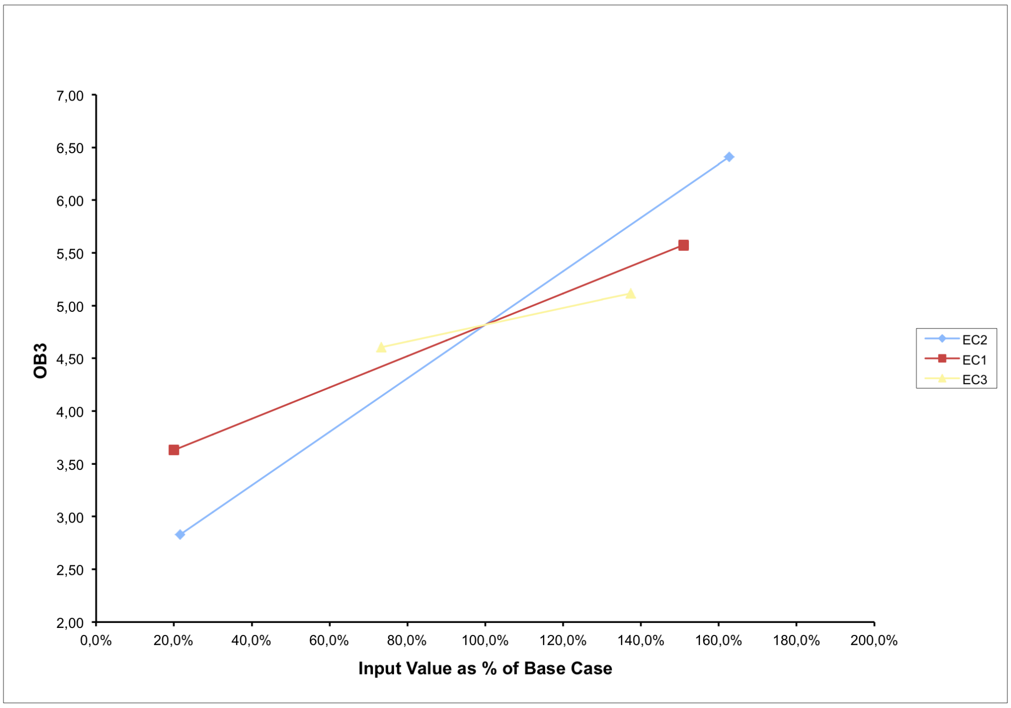


Figure B.51: Sensitivity analysis of External Characteristics with respect to OB3: spider chart.

B.2.2 Internal Analysis

B.2.2.1 IC vs OB1

Figures B.52, B.53 and B.54 show sensitivity analysis of External Characteristics with respect to OB1.

	Corresponding Input Value			OB1 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
IC2	3,2	4,9	7,9	4,3	5,2	6,9	2,5	81,6%
IC3	3	5,4	7,4	4,7	5,2	5,7	0,9	10,8%
IC1	4,8	5,8	7,9	5,0	5,2	5,8	0,8	7,6%

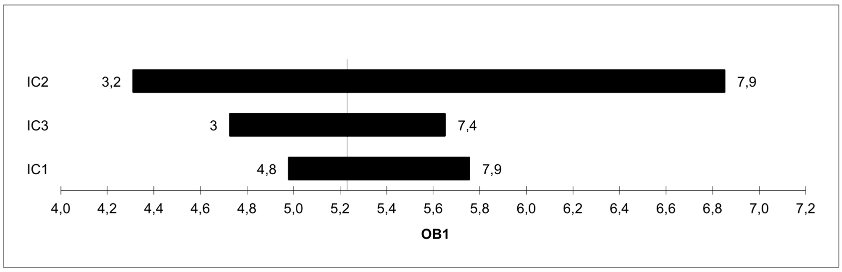


Figure B.52: Sensitivity analysis of External Characteristics with respect to OB1: tornado diagram.

	Corresponding Input Values			OB1 Output Value			
Input Variables	Low Output	Base Case	High Output	Low	Base	High	Swing
IC2 & IC3	3,2 & 3	4,9 & 5,4	7,9 & 7,4	3,8	5,2	7,3	3,5
IC1 & IC2	4,8 & 3,2	5,8 & 4,9	7,9 & 7,9	4,1	5,2	7,4	3,3
IC1 & IC3	4,8 & 3	5,8 & 5,4	7,9 & 7,4	4,5	5,2	6,2	1,7

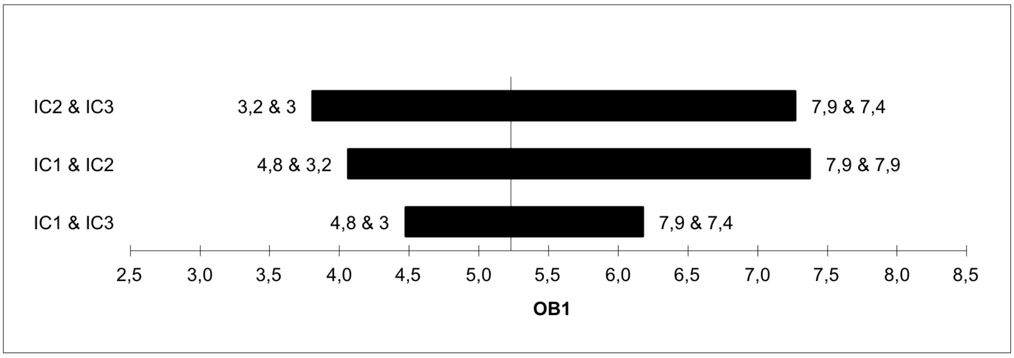


Figure B.53: Sensitivity analysis of External Characteristics with respect to OB1: two factors tornado diagram.

Input Variable	Corresponding Input Value Low Output	Base Case	High Output	Input Value as % of Base Low %	Base %	High %	OB1 Output Value Low	Base	High	Swing
IC2	3,2	4,9	7,9	65,3%	100,0%	161,2%	4,3	5,2	6,9	2,5
IC3	3	5,4	7,4	55,6%	100,0%	137,0%	4,7	5,2	5,7	0,9
IC1	4,8	5,8	7,9	82,8%	100,0%	136,2%	5,0	5,2	5,8	0,8

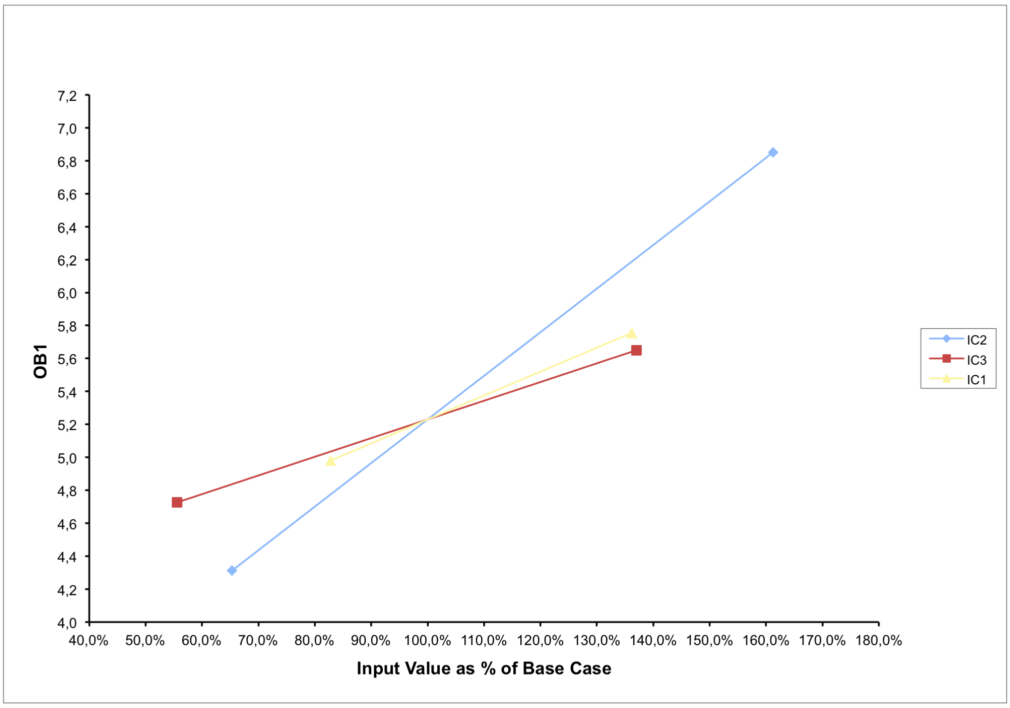


Figure B.54: Sensitivity analysis of External Characteristics with respect to OB1: spider chart.

B.2.2.2 IC vs OB2

Figures B.55, B.56 and B.57 show sensitivity analysis of External Characteristics with respect to OB2.

Input Variable	Corresponding Input Value Low Output	Base Case	High Output	OB2 Output Value Low	Base	High	Swing	Percent Swing^2
IC3	3	5,8	7,3	4,7	5,6	6,1	1,4	41,2%
IC2	3,4	4,9	7,7	5,2	5,6	6,5	1,3	34,0%
IC1	4,9	5,9	7,8	5,2	5,6	6,3	1,1	24,8%

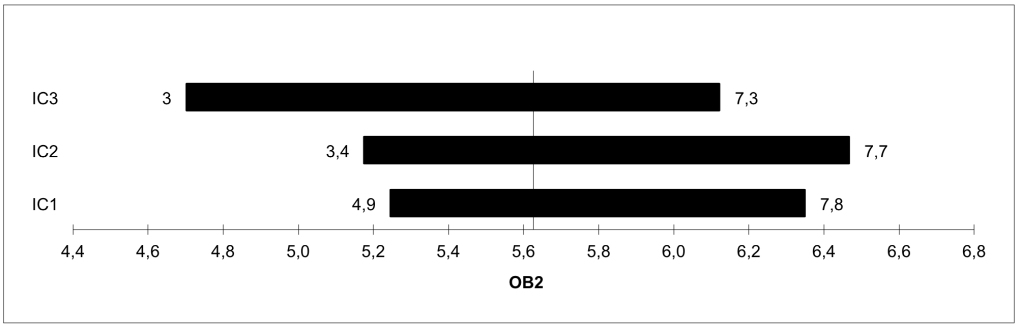


Figure B.55: Sensitivity analysis of External Characteristics with respect to OB2: tornado diagram.

Input Variables	Corresponding Input Values: Low Output	Base Case	High Output	OB2 Output Value: Low	Base	High	Swing
IC2 & IC3	3,4 & 3	4,9 & 5,8	7,7 & 7,3	4,3	5,6	7,0	2,7
IC1 & IC3	4,9 & 3	5,9 & 5,8	7,8 & 7,3	4,3	5,6	6,8	2,5
IC1 & IC2	4,9 & 3,4	5,9 & 4,9	7,8 & 7,7	4,8	5,6	7,2	2,4

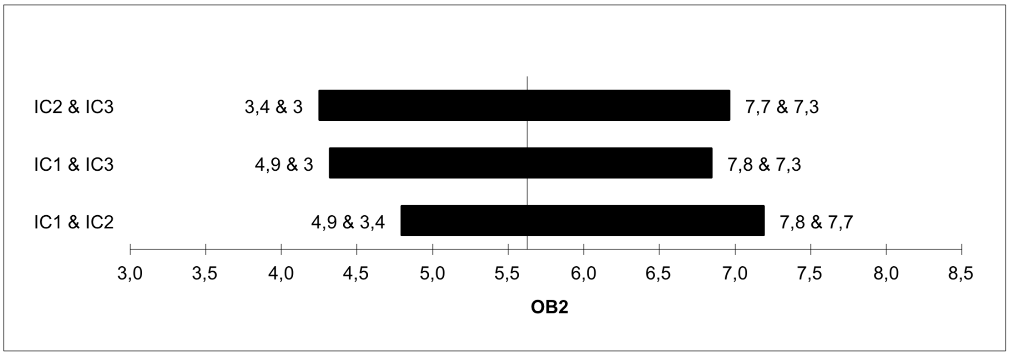


Figure B.56: Sensitivity analysis of External Characteristics with respect to OB2: two factors tornado diagram.

Input Variable	Corresponding Input Value: Low Output	Base Case	High Output	Input Value as % of Base: Low %	Base %	High %	OB2 Output Value: Low	Base	High	Swing
IC3	3	5,8	7,3	51,7%	100,0%	125,9%	4,7	5,6	6,1	1,4
IC2	3,4	4,9	7,7	69,4%	100,0%	157,1%	5,2	5,6	6,5	1,3
IC1	4,9	5,9	7,8	83,1%	100,0%	132,2%	5,2	5,6	6,3	1,1

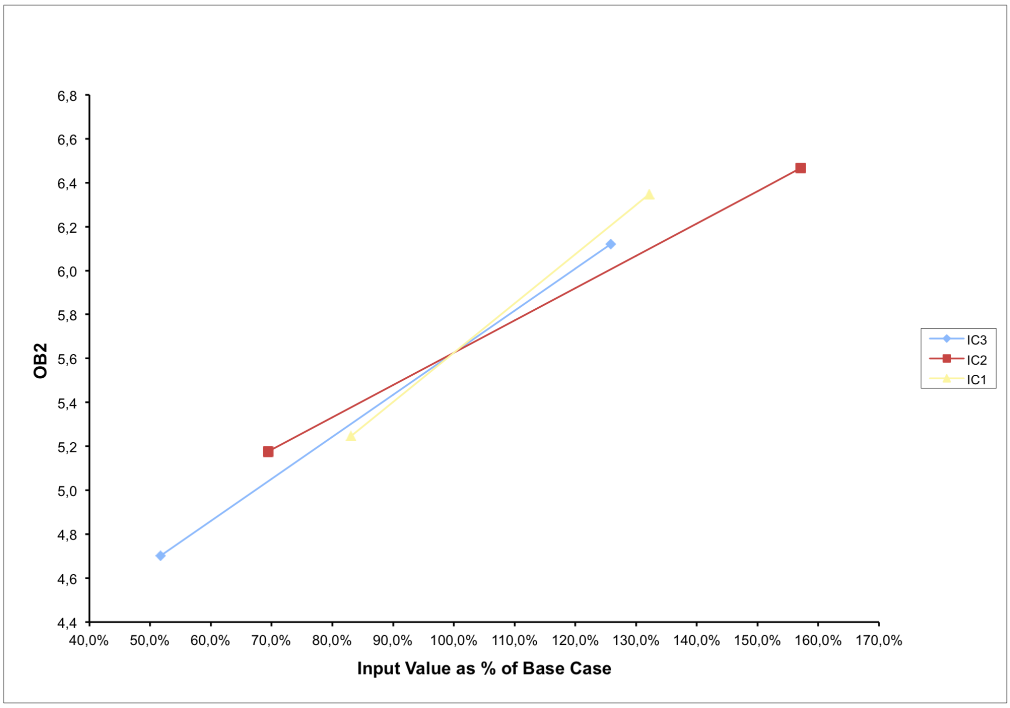


Figure B.57: Sensitivity analysis of External Characteristics with respect to OB2: spider chart.

B.2.2.3 IC vs OB3

Figures B.58, B.59 and B.60 show sensitivity analysis of External Characteristics with respect to OB3.

	Corresponding Input Value			OB3 Output Value				Percent
Input Variable	Low Output	Base Case	High Output	Low	Base	High	Swing	Swing^2
IC1	4,9	6,1	8,2	5,3	5,9	6,9	1,7	53,8%
IC3	3	6,2	7,2	4,8	5,9	6,2	1,4	38,0%
IC2	3,2	4,6	7	5,6	5,9	6,3	0,6	8,2%

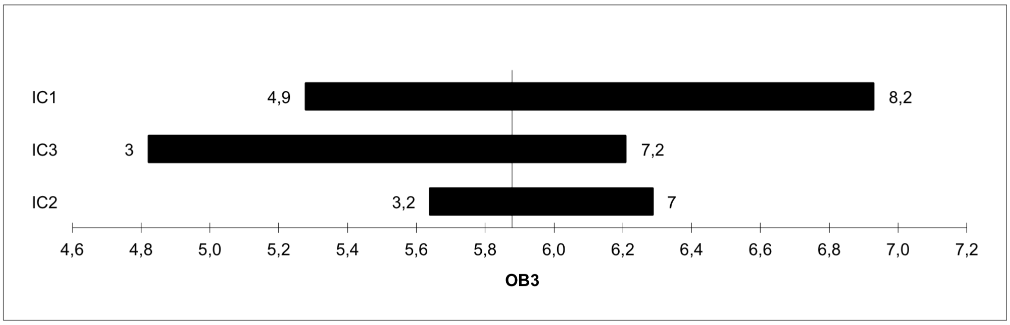


Figure B.58: Sensitivity analysis of External Characteristics with respect to OB3: tornado diagram.

	Corresponding Input Values			OB3 Output Value			
Input Variables	Low Output	Base Case	High Output	Low	Base	High	Swing
IC1 & IC3	4,9 & 3	6,1 & 6,2	8,2 & 7,2	4,2	5,9	7,3	3,0
IC1 & IC2	4,9 & 3,2	6,1 & 4,6	8,2 & 7	5,0	5,9	7,3	2,3
IC2 & IC3	3,2 & 3	4,6 & 6,2	7 & 7,2	4,6	5,9	6,6	2,0

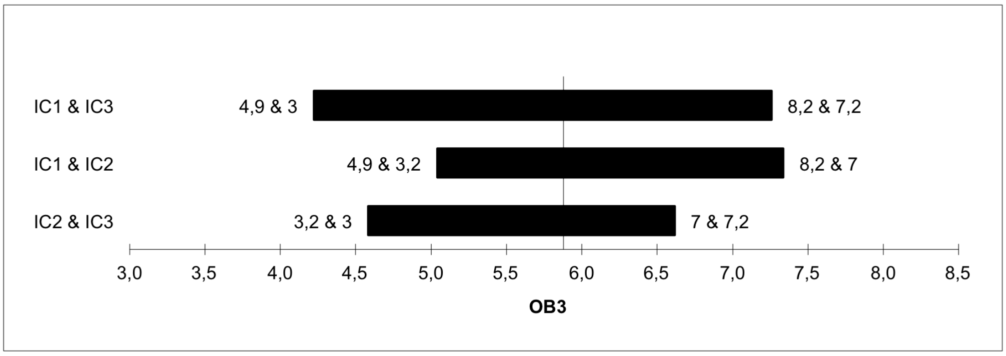


Figure B.59: Sensitivity analysis of External Characteristics with respect to OB3: two factors tornado diagram.

	Corresponding Input Value			Input Value as % of Base			OB3 Output Value			
Input Variable	Low Output	Base Case	High Output	Low %	Base %	High %	Low	Base	High	Swing
IC1	4,9	6,1	8,2	80,3%	100,0%	134,4%	5,3	5,9	6,9	1,7
IC3	3	6,2	7,2	48,4%	100,0%	116,1%	4,8	5,9	6,2	1,4
IC2	3,2	4,6	7	69,6%	100,0%	152,2%	5,6	5,9	6,3	0,6

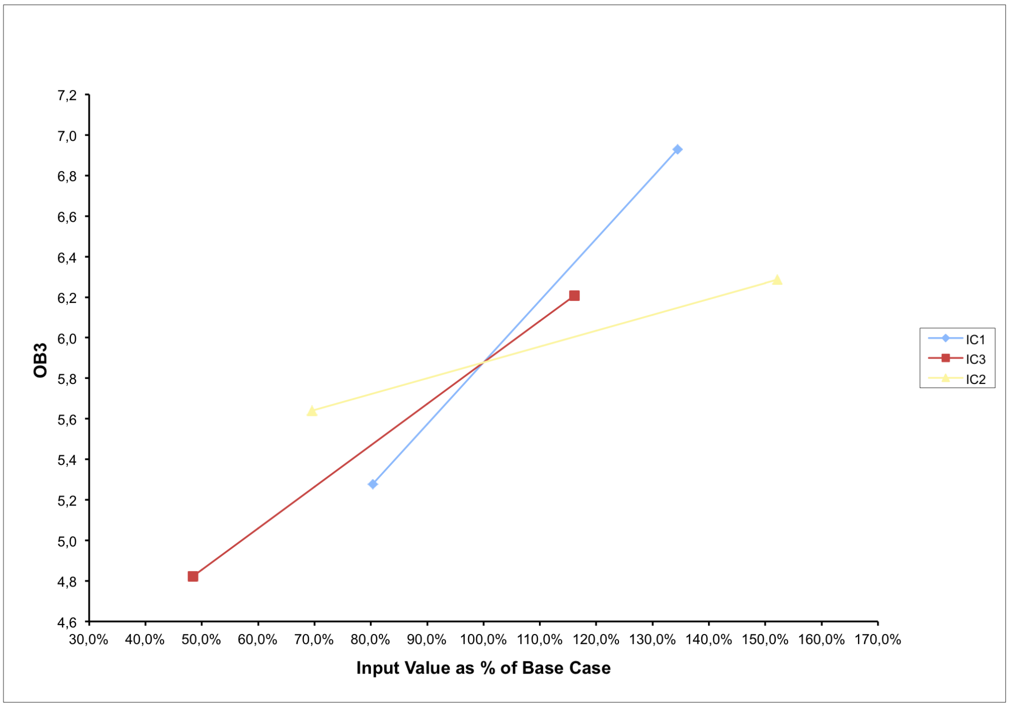


Figure B.60: Sensitivity analysis of External Characteristics with respect to OB3: spider chart.

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